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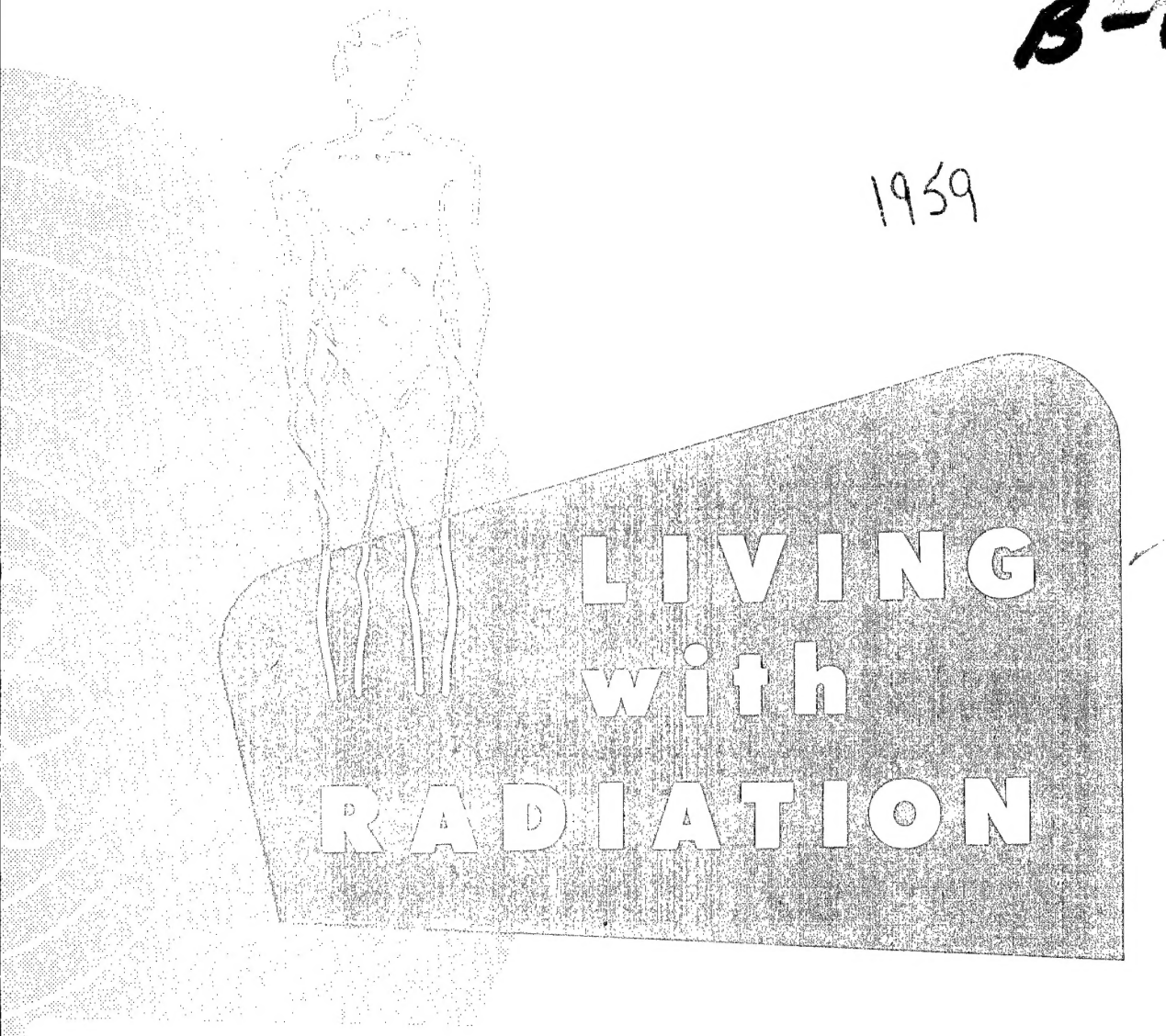

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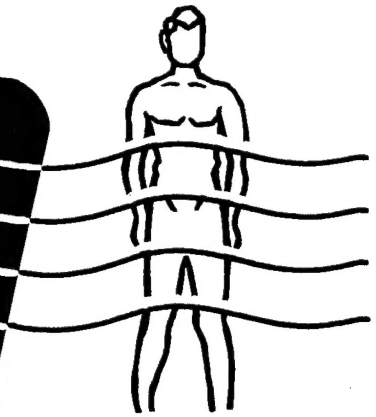
Living with RADIATION



The PROBLEMS OF THE NUCLEAR AGE for the LAYMAN

Prepared by

FRANCIS L. BRANNIGAN

SAFETY & FIRE PROTECTION BRANCH • OFFICE OF INDUSTRIAL RELATIONS • WASHINGTON, D. C.

UNITED STATES ATOMIC ENERGY COMMISSION

PREFACE

Part I of "Living With Radiation" presents the essence of what has been found by extensive field experience to be a practical approach to the understanding of the industrial radiation hazard.

It is intended for a layman who requires a basic understanding of the relationship of the radiation problem to his own field—because of its direct bearing on his own work or because he is an instructor of others.

The technically educated reader should bear in mind that the intention is not to make a technician out of the student, rather it is to present only what he needs to know, without the frustration engendered by the precise detailed exposition necessary to the scientist.

The material has been used successfully as the basic foundation of the 3-day Instructor Courses conducted by the Safety and Fire Protection Branch for fire and police instructors and others with a real need for practical information.

Texts applying the material in Part I to specific problems in fields of work such as fire, police transportation, etc., will be issued as a series of Parts II. Each Part II will relate the basic material to one particular field

Constructive comments and suggestions are invited.

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Chapter 1

INTRODUCTION

The subject of ionizing radiation and its effects is extremely confusing to the average layman. Much that appears in newspapers and magazines is written with an eye to the sensational and presents the hazard of radiation as if its unique aspects make it impossible to understand and so set it apart from all the other hazards of normal, everyday, existence. The result is that the average individual feels that only a highly skilled technician can understand this extremely complex subject, and he either ignores the entire subject and the possibility of hazard to himself, or, on the other hand, has an unreasonable fear of radiation injury in situations where in fact no real hazard exists.

The purpose of this text is to present to you a layman's understanding of the hazards of radiation. You, in turn, can then pass on the information about the hazards and the precautions to be taken to avoid unnecessary exposure. As an end result, the radiation hazard will be placed in proper perspective to the other hazards of our workaday world.

You will learn some fundamental necessary facts and many common misconceptions will be cleared away. All of the material will be presented in a manner and in a language which you can, if you choose, adopt as your own. Many people, attempting to teach this subject, feel that it is first necessary to define all of the appropriate terms in the field of physics so that the student will have an accurate understanding of precisely what each word means, and from that point go forward to an understanding of the subject. The difficulty is that the instructor has spent many years building up in his mind an exact understanding of what particular words mean, but the fact that he defines such a word for the students does not mean that the word means the same thing to the students as it does to the instructor, or that the student immediately has an exact concept of what the instructor means when he uses a particular word.

Think of the difference between a translating knowledge of a foreign language and knowing the language well enough to think in it. If you go to a foreign country with only your high school ability to translate the language, you find that the person to whom you speak presents so many words and ideas so rapidly to you that you are completely overwhelmed, and that by the time you attempt to finish the translation of the first idea, he has gone on to several more, and you are hopelessly lost.

In this presentation, we will not necessarily precisely define our terms, but we will try to use working concepts, because this is the natural method which we followed in learning in childhood. When, as a child, we discovered in the living room an object that was flat on the top and had some legs on it, we went to mother and said, "What is this?" She said, "A table." From that point on, we had a concept of a table. We know what a table is, we know also what is not a table, yet we would find it difficult to define a table in precise terms. "A flat surface with 4 legs," you say? There are tables with any number of legs. "A flat surface?" A draftsman works on a drafting table, which has a sloping surface. Yet, despite the fact that we cannot define it, we all are quite sure that we know what a table is, because we have a working concept.

We will get some working concepts of physical phenomena which will serve quite well to accomplish our purpose. In some cases, we may not be as precisely accurate as the physicist must be, but we will be accurate enough to accomplish our purpose.

The atomic age promises many wonderful benefits for mankind. The use of atomic power, the use of radioactive materials as tracers in biology and in industry, the use of massive doses of radiation in the cure of malignant diseases, the use of radiation to kill off bacteria in food so that food may be preserved longer, the use of the energy from radioactive material in certain chemical processes to bring about the development of new and useful products—all these things promise great benefits to mankind, yet one single fact makes it necessary for us to undertake our study.

Radioactive materials emit energy which has the power to damage living tissue.

Chapter II

THE BENEFITS OF THE ATOMIC AGE

Since there is, admittedly, some hazard in the use of radioactive materials, let us examine briefly the benefits to mankind which flow from the development of nuclear energy.

There are many, many useful applications of radiation for the benefit of mankind. In this discussion we cite only a few, but we do attempt to break them down categorically so that, as you learn of other uses of radioisotopes, you may be able to fill them in under their proper headings. This categorical breakdown is useful in eliminating confusion. You will find, for instance, a great deal of confusion between the diagnostic and therapeutic uses of radioisotopes; that is, the use of radioisotopes to discover the nature of a particular illness as distinguished from the use of radioisotopes to cure the illness. In some cases, as soon as a person hears that radioisotopes are involved, there is a natural inclination to jump to the conclusion that the patient necessarily has cancer because of the fact that the use of radiation in the cure of cancer is very widely known to the public.

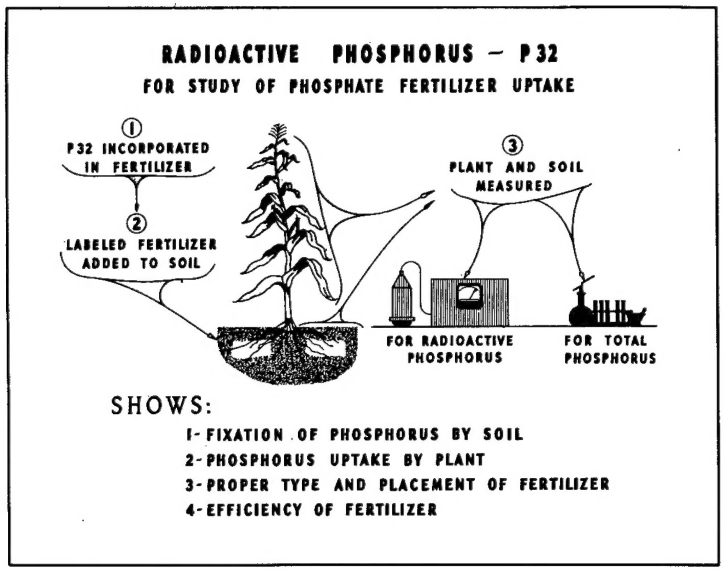
The first use that we find for radioactive materials is that they send out signals which can be detected by electrical or chemical means, and this use, of itself, makes them extremely beneficial to mankind.

For instance, it makes it possible to trace biological processes in man, animal, and plants. The thyroid gland is a very important gland in the body. It is well known to medical men that the thyroid gland will take up practically all of the element iodine which enters the body. If we introduce radioactive iodine into the body, is it still, chemically, iodine, and, therefore, it will go to the thyroid gland. By the use of electrical counting devices, the surgeon can determine whether the thyroid is properly functioning, as he compares the radioactivity recorded with what it should be. The radioactive iodine is not doing anything for the patient or doing anything to the thyroid condition from which the patient is suffering. In this case, it is simply being used as a tool to tell the doctor whether the thyroid is functioning properly. What to do about the thyroid condition is another matter entirely.

There are many, many other uses of isotopes as tracers in medicine. New uses are being discovered every day.

One of the most pressing problems facing the world today is the explosive growth of population and the necessity for feeding, adequately, more and more people every year. The application of scientific principles to the production of foodstuffs for mankind is only in its infancy. Much of our feeding of food animals and plants intended for human or food animal consumption is, in truth, done at random. By the use of radioactive tracers, scientific knowledge can take the place of guesswork, and we will be able to produce much more food. This is of the utmost importance in a world in which many people go to bed hungry every night. As a typical instance, the use of calcium and phosphorus tracers have provided information which will enable livestock feeders to get maximum efficiency from feed by more careful control of the calcium-phosphorus ratio of the diet, and by eliminating high concentration of elements which affect adversely the absorption of these elements.

Radioisotopes have proven extremely useful in determining the nature and extent of possible toxic residues in or on agricultural commodities from the use of insecticide compounds. Work with radioactive isotopes has shown that


RADIOACTIVE PHOSPHORUS – P32
FOR STUDY OF PHOSPHATE FERTILIZER UPTAKE
① P32 INCORPORATED IN FERTILIZER
② LABELED FERTILIZER ADDED TO SOIL
③ PLANT AND SOIL MEASURED
FOR RADIOACTIVE PHOSPHORUS
FOR TOTAL PHOSPHORUS
SHOWS:
1- FIXATION OF PHOSPHORUS BY SOIL
2- PHOSPHORUS UPTAKE BY PLANT
3- PROPER TYPE AND PLACEMENT OF FERTILIZER
4- EFFICIENCY OF FERTILIZER

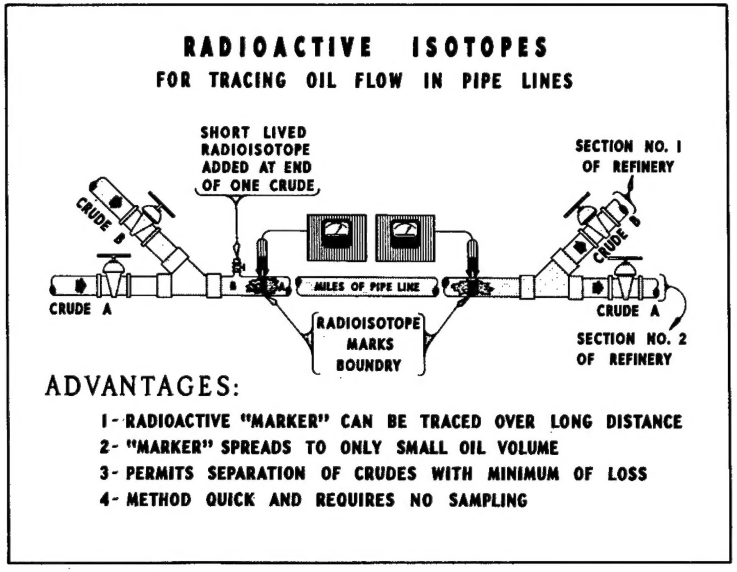
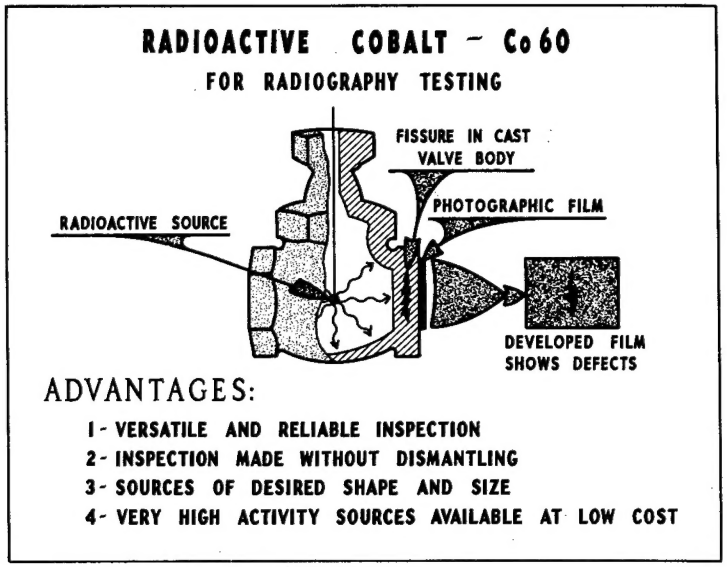
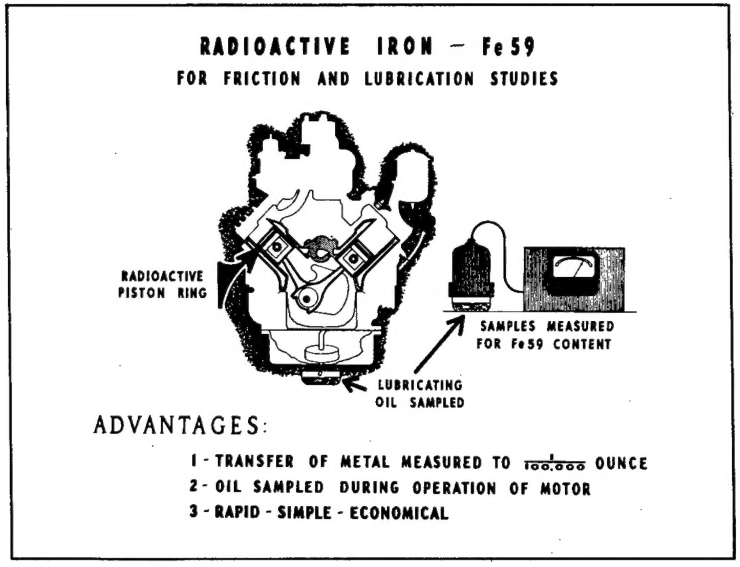

RADIOACTIVE ISOTOPES
FOR TRACING OIL FLOW IN PIPE LINES
SHORT LIVED RADIOISOTOPE ADDED AT END OF ONE CRUDE
SECTION NO. 1 OF REFINERY
CRUDE B
CRUDE A
MILES OF PIPE LINE
RADIOISOTOPE MARKS BOUNDRY
SECTION NO. 2 OF REFINERY
ADVANTAGES:
1- RADIOACTIVE "MARKER" CAN BE TRACED OVER LONG DISTANCE
2- "MARKER" SPREADS TO ONLY SMALL OIL VOLUME
3- PERMITS SEPARATION OF CRUDES WITH MINIMUM OF LOSS
4- METHOD QUICK AND REQUIRES NO SAMPLING

FIGURE 1


RADIOACTIVE COBALT – Co 60
FOR RADIOGRAPHY TESTING
FISSURE IN CAST VALVE BODY
PHOTOGRAPHIC FILM
RADIOACTIVE SOURCE
DEVELOPED FILM SHOWS DEFECTS
ADVANTAGES:
1- VERSATILE AND RELIABLE INSPECTION
2- INSPECTION MADE WITHOUT DISMANTLING
3- SOURCES OF DESIRED SHAPE AND SIZE
4- VERY HIGH ACTIVITY SOURCES AVAILABLE AT LOW COST


RADIOACTIVE IRON – Fe 59
FOR FRICTION AND LUBRICATION STUDIES
RADIOACTIVE PISTON RING
SAMPLES MEASURED FOR Fe 59 CONTENT
LUBRICATING OIL SAMPLED
ADVANTAGES:
1- TRANSFER OF METAL MEASURED TO 1/100,000 OUNCE
2- OIL SAMPLED DURING OPERATION OF MOTOR
3- RAPID - SIMPLE - ECONOMICAL

many fertilizers can be applied directly to the leaves of plants and be absorbed through the leaves. It has also shown that fertilizer, taken up through the root system, can be leached from the leaves by rain.

Just as we can trace biological processes in man and plants and animals, we can trace physical processes by making some of the material radioactive, or by including radioactive material similar to the materials which we wish to trace. A simple example is the use of radioactive iron to check engine wear. The piston ring is made of radioactive iron. As the piston ring wears, the radioactive iron is detected in the lubricating oil system. Another use is the addition of radioactive isotopes to the product transported in oil pipe lines. The radioactive material is introduced at the interface, between two different shipments, and provides a means by which one shipment can be differentiated immediately from the next shipment.

It is very important to us, at times, to know exactly how dense a material is and whether the density is uniform throughout the material. An example of this is the examination of piping which must hold against very high pressures. When such piping is hydrostatically tested, we have simply determined that the piping did not fail at the pressure reached on the date of the test. Hydrostatic testing does not show us whether there is a potential fault which may fail at a later date. We are familiar with the fact that valves and other such fittings can be X-rayed to determine whether or not there is any defect in the body of the valve. It is impossible to take an X-ray machine into the field to make an X-ray of a weld in a pipe.

Radioactive materials are used for this purpose. Radioactive cobalt, for instance, is inserted into the pipe at the location of the weld. The weld is surrounded with X-ray film. The film is sensitive to the radiation coming through the pipe. If some parts of the weld are not as dense as the rest of the weld, less radiation will be absorbed, the film will receive more radiation, and, therefore, the film will be darker.

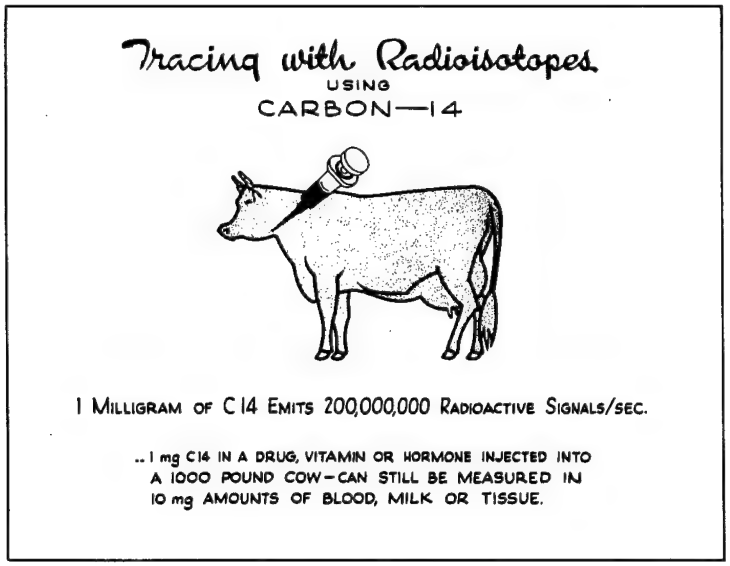
The difference in absorption of radiation by various thicknesses of materials is also used in so-called thickness-guages. These are extremely important in industries such as metal-working, where metals must be rolled to an exact thickness at high speed. If the manufacturer waits to determine whether the material is the proper thickness until the entire roll has been manufactured, he may find that he has a serious loss. The thickness-gauge makes it possible to determine immediately whether the material is being rolled to the proper thickness.

All of these uses are applications of the fact that radioactive materials send out signals which can be detected either electrically or chemically.

The next category of use for radioisotopes is the fact that they have the characteristic of making the air electrically conductive. The accumulation of static electricity is a serious hazard in those areas where an explosive vapor-air concentration may exist. Static electricity is also a nuisance industrially because it makes things stick together. Static electricity can be removed by grounding the equipment, or, in some cases, by surrounding it with a humid atmosphere. In some uses, however, neither of these methods is satisfactory.

In the use of radioactive static eliminators, the rays from the radioactive material ionize the air, and, thus, an invisible path is provided through which the electricity can flow to ground. It is not necessary that there be any contact with the material.

Another very important use of radioactive materials is the fact that they emit energy which can bring about the destruction of living cells. It is in this property that we find the entire hazard of the use of radioactive materials. However, for the moment, let us pass by the hazard, and let us consider the beneficial effects.


Tracing with Radioisotopes
USING
CARBON—14
1 MILLIGRAM OF C 14 EMITS 200,000,000 RADIOACTIVE SIGNALS/SEC.
.. 1 mg C14 IN A DRUG, VITAMIN OR HORMONE INJECTED INTO A 1000 POUND COW—CAN STILL BE MEASURED IN 10 mg AMOUNTS OF BLOOD, MILK OR TISSUE.

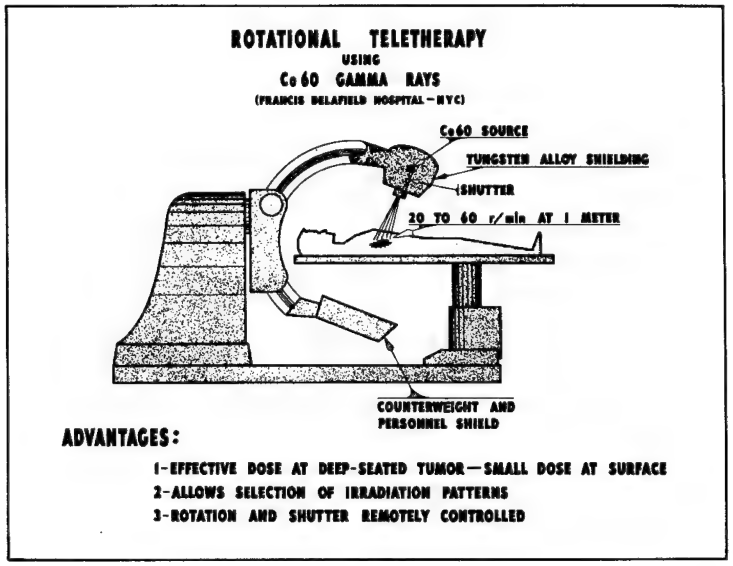
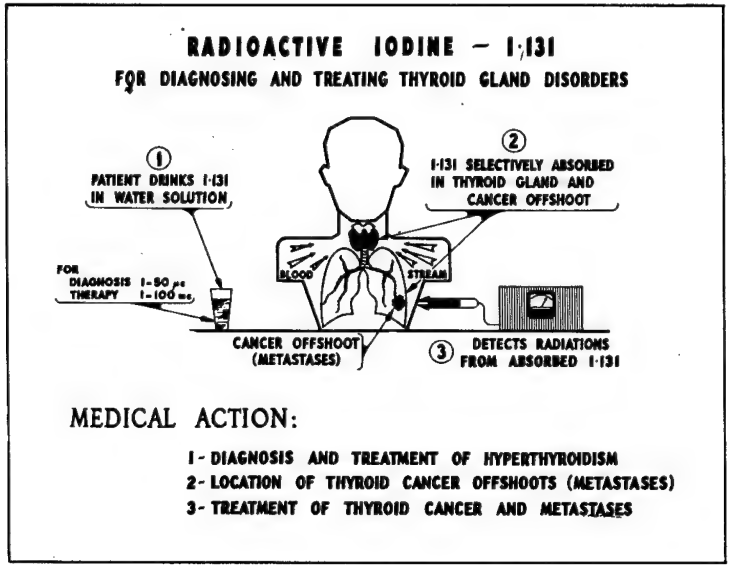
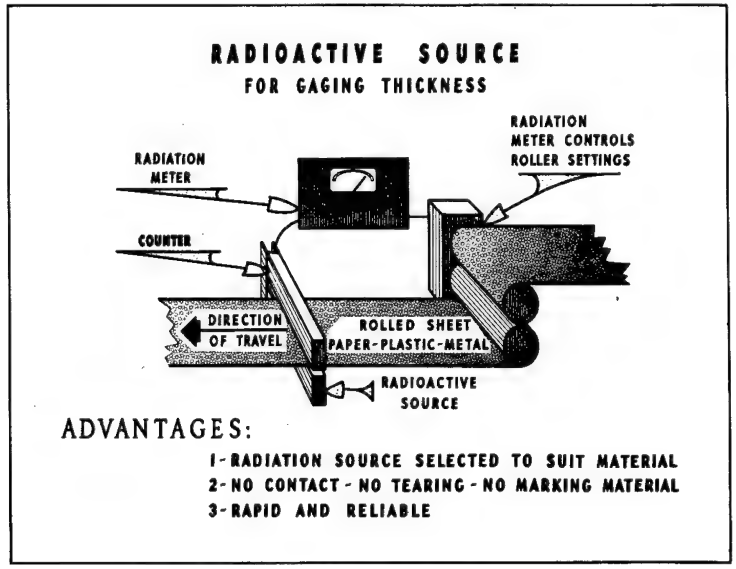

ROTATIONAL TELETHERAPY
USING
Co 60 GAMMA RAYS
(FRANCIS DELAFIELD HOSPITAL—NYC)
Co60 SOURCE
TUNGSTEN ALLOY SHIELDING
SHUTTER
20 TO 60 r/min AT 1 METER
COUNTERWEIGHT AND PERSONNEL SHIELD
ADVANTAGES:
1-EFFECTIVE DOSE AT DEEP-SEATED TUMOR—SMALL DOSE AT SURFACE
2-ALLOWS SELECTION OF IRRADIATION PATTERNS
3-ROTATION AND SHUTTER REMOTELY CONTROLLED

FIGURE 2


RADIOACTIVE IODINE — I-131
FOR DIAGNOSING AND TREATING THYROID GLAND DISORDERS
1 PATIENT DRINKS I-131 IN WATER SOLUTION
2 I-131 SELECTIVELY ABSORBED IN THYROID GLAND AND CANCER OFFSHOOT
FOR DIAGNOSIS I-50 μc
THERAPY I-100 mc
BLOOD STREAM
CANCER OFFSHOOT (METASTASES)
3 DETECTS RADIATIONS FROM ABSORBED I-131
MEDICAL ACTION:
1-DIAGNOSIS AND TREATMENT OF HYPERTHYROIDISM
2-LOCATION OF THYROID CANCER OFFSHOOTS (METASTASES)
3-TREATMENT OF THYROID CANCER AND METASTASES


RADIOACTIVE SOURCE
FOR GAGING THICKNESS
RADIATION METER
RADIATION METER CONTROLS ROLLER SETTINGS
COUNTER
DIRECTION OF TRAVEL
ROLLED SHEET PAPER-PLASTIC-METAL
RADIOACTIVE SOURCE
ADVANTAGES:
1-RADIATION SOURCE SELECTED TO SUIT MATERIAL
2-NO CONTACT-NO TEARING-NO MARKING MATERIAL
3-RAPID AND RELIABLE

A simple description of a cancer is that it is a group of cells growing much too rapidly. Radiation is used to kill off the rapidly growing tissues, and, therefore, bring about a cure, or, at least, an alleviation of the cancer. You will find, however, that there is much confusion on this subject, and that there are people who believe that there is a direct relationship between radiation and cancer, as such. For instance, a man employed on a pipeline in Texas where radium was being used for radiography of welds knew that radium was used to cure cancer. His mother-in-law had cancer. He took the radium home in his pocket intending to use it to cure his mother-in-law's cancer. Contrary to what he apparently believed, the radium made no distinction between the sound tissue of his leg and his mother-in-law's cancer. The result was that he received severe radiation burns to his leg, necessitating its amputation. This confusion may bring about other instances of this type, and radiation sources, which might be accessible to people who have a very limited knowledge of their use and hazard, should be carefully controlled to prevent such incidents from taking place.

Another use for the energy from radioactive materials to destroy living tissue is in the sterilization of food and drugs. Food and drugs are sealed in moistureproof wrappers to prevent any contact with the outside air. They can then be subjected to massive doses of radiation so that all living organisms in the package are killed off.

If all of the organisms are killed off, the food is sterilized. If a lesser dose of radiation is used, the food can be pasteurized. That is, not all of the organisms are killed off, but sufficient are killed so that the food can be stored for a reasonable time without destruction by bacteria. The food itself is not radioactive any more than you are radioactive after you have been X-rayed. There is, of course, a great deal of experimental work yet to be done. In some foods, there are very marked changes in color and flavor. In other foods, the changes are much less pronounced. The Quartermaster Corps of the Army, which is responsible for food research for all of the Military Services, is actively carrying forward a research program.

Radiation sterilization is used in the manufacture of drugs. Destruction of bacteria by heat in many cases isn't practical because the heat will also damage the drug. Radiation kills off the bacteria without raising the temperature of the drugs.

The next use that we find for the energy from radioactive materials is that this radiation energy can be used to excite the atoms of certain materials. We are all familiar with radium-dial wrist watches. It is generally believed that it is the radium which glows in the dark. This is not so, but the radioactive materials emit energy which causes a phosphor, such as zinc sulfide, to glow in the dark.

A much more important use of this phenomenon is in the field of chemical processing. By the use of radiation energy, certain chemical effects can be brought about, thus giving us a better product. For instance, when polyethylene was first developed, it could not be subjected to boiling water temperature. Now, at the proper point in the process, the polyethylene is subjected to the radiation energy from radioactive materials. This knocks out a couple of hydrogen atoms, which go off as gas, and changes the manner in which the atoms of polyethylene are linked together, producing so-called cross-linked polyethylene. This can be subject to boiling water temperature, and, thus, can be used in many applications as a substitute for glass where the container must be sterilized, such as for baby bottles.

Another use for the energy of radioactive materials is voltage production. This is the direct production of electricity from the energy released from the radioactive atoms. Don't confuse this with the indirect production of electrical energy in power reactors, where

we convert the fission energy to heat and then to conventional forms of power. The quantity of energy is extremely minute, but the so-called atomic battery does have uses where a dependable source of elecrical energy in small quantities is required.

Radiation Energy vs. Fission Energy

In all of the uses thus far, we have been discussing the use of the energy naturally emitted by the decay of radioactive materials. Some of these uses are shown in figures 1 and 2.

Certain materials have the characteristic of being able to emit bits of matter, which, when they strike other atoms of the same matter, cause those atoms to break open and emit more bits of matter which continue the so-called chain reaction process. The thing that makes this useful to mankind is the fact that, when these atoms are split open, a certain amount of the energy, which has been holding the atom together, is released, and this energy can be harnessed. This is *fission energy*, and should not be confused with *radiation energy*. The regrouping of the atomic material also makes new atoms, many of which are radioactive. Therefore, we get both energy and new arrangements of the atoms, that is to say, new elements.

We may be seeking, primarily, the energy release, as we are in a power reactor or in an atomic bomb. As a byproduct, we will get the new atoms, which are called fission products. Some of these fission products are dangerously radioactive. In an atomic reactor, the fission products must be removed periodically, and the problem of how to handle them creates one of the problems of the use of atomic fuels.

In a production reactor in which we are creating a new element on a "mass production" basis, such as the plutonium production reactors at Hanford, or in a research reactor where we are creating new elements for any of the applications of radioisotopes which we discussed previously, energy is also liberated. In many cases, it is not possible to use this energy economically, and, therefore, it is simply wasted by being absorbed in the form of heat by air or water.

The atomic fission process, therefore, is used to make the radioactive materials which are useful to us in the ways which we have discussed earlier in this section, or for the generation of electrical power. Electrical power is the basis of our standard of living. We need only to think back to our own childhood days and to the limited use of electricity in our homes. The author remembers the furor some years ago when the local utility company proposed a minimum electrical charge based upon the use of 10 kilowatt hours per month. There was a great public clamor on the basis that this charge was entirely unjust to the thousands in the city which did not use this "tremendous" quantity of electricity each month.

While the use of electrical energy to maintain our standard of living is more apparent to us in the use of household appliances, actually, it is in the industrial use of electricity for production that we find the real basis of our high standard of living. The development of alternating current made it possible to use energy at quite some distance from the point where it was created. During peak water-flow times, for instance, electrical power generated by hydroelectric facilities at Niagara Falls is transmitted over the wires to New York City where it is used.

There is an interesting historical parallel between radiation and electricity. When Tesla and Westinghouse developed the use of alternating current, they were violently opposed by Edison's associates. As a matter of fact, an advertising campaign featured the fact that the State of New York was using alternating current to execute criminals, thus "proving" alternating current was much too unsafe to be used.

Man needed alternating current for the development of his standard of living, and he

learned to handle it safely. Man needs the peace time uses of atomic energy, and he will likewise learn to handle them safely.

The achievements of the Nautilus and our other atomic-powered submarines are breath-taking, even in this day of Sputniks and moon rockets. The fact that the very first atomic submarine is a highly efficient operational unit of the fleet can be appreciated more if we realize that it is equivalent to Robert Fulton having designed and built the Queen Mary as his first ship rather than the Clermont.

Chapter III

THE PROBLEM OF HAZARD

Radioactive materials emit energy which has the power to damage living tissue.

The relationship between this property of radioactive materials and the problem of using them for mankind's benefit can best be set forth in the following manner:

All radiation can do damage to the body if received in sufficient quantity.

Within certain limits, damage can be repaired by the body so that there is no apparent effect.

Therefore, when it is known that these limits can be maintained, it is reasonable for people to expose themselves to radiation in order to accomplish necessary work.

But, it follows that the degree of exposure should be related to the importance of the work being accomplished.

That is nice philosophy, you say! But I don't care to be exposed to any of this radiation hazard. I have heard all sorts of things about it, and I don't want to take any chances, and I don't want any exposure to radiation at all. Unfortunately, we cannot avoid exposure to radiation. We are all exposed to radiation from outer space, cosmic radiation, which increases in intensity as we go up in altitude. For instance, in Denver, Colo., the mile-high city, we would receive twice the radiation from cosmic rays that we would receive at sea level. Let's get away from cosmic radiation and go down deep in a mine where no cosmic radiation can penetrate. We still haven't solved the problem, because then we are exposed to radiation from radioactive material in the earth's crust. In addition, there are radioactive elements within the make-up of our own bodies, elements that have been radioactive from the beginning of time, such as radioactive potassium, radium, and radioactive carbon. Our bodies also tend to concentrate radioactive materials that we take into our bodies, particularly from the water which we drink. Water, in some parts of the country, particularly from some mineral springs, has appreciable radioactivity. So, from the beginning of time, man has been exposed to inescapable natural radiation.

In addition to the natural background of radiation, the population as a whole receives a certain amount of radiation from medical diagnostic and therapeutic procedures. It is obvious from our basic premise that radiation can damage living tissue, that some of this medical and dental radiation may have some harmful effects. However, we balance this harmful effect against the good we expect to accomplish from the medical procedure. If we find a specific medical procedure in which the hazard is not outweighed by the good received, the logical course is to modify this specific procedure, not to do away with all radiation exposure.

An example of foolish and unnecessary exposure to radiation is the use of shoe-fitting machines which fit children's shoes by the use of X-rays. These are a hazard, not only to the child, but to the shoe clerk. No useful purpose is served which could not be served by other means, and in many jurisdictions these devices have been outlawed.

Probably the chief error in much of our current thinking about radiation hazards is the failure to relate radiation hazards to the other hazards of human existence. All human activity involves risks. Some of them are physical, such as the hazard of being hit on the head with a heavy object dropped from above. Some hazards are more mental than physical, such as those of the advertising executive or play producer, who is under the constant strain of delivering completely satisfactory work or suffering the penalty of being ruthlessly eliminated. Consciously or not, when we

select our field of work, we make an appraisal of the hazards involved, along with the other factors, such as pay, general working conditions, prospects for advancement, security of employment, which we consider. Each occupation has its own peculiar hazards, inherent in the nature of the work. In controlling the hazard, we attempt to reduce the probability of accident to a minimum but cannot guarantee absolute freedom from risk.

When thinking about radiation hazard, however, some people seem to regard it as a hazard apart from all other hazards, and demand that we be absolutely safe from it. In no field of human existence is there absolute safety. In everything that we do, we weigh the hazard against the good to be accomplished, consciously or unconsciously, and make a determination.

We are, for instance, all quite familiar with the fact that serious diseases can be spread from person to person by improperly washed tableware. Yet, most of us would consider a man who went into a restaurant and applied a sterilizing solution to the tableware offered to him before he used it, to be somewhat neurotic, to say the least. In general, we have weighed the risk and found that it is so slight that we prefer to ignore it.

However, if a violent epidemic were to break out in our city, we might well consider that we should take such precautions, and that a person who wouldn't take such precautions is lacking in common sense and good judgment.

When we drive on the highway, despite the fact that we might maintain our own automobile in perfect mechanical condition, despite the fact that we might be a truly defensive driver and mentally drive not only our own car but the other cars that the defensive driver must "drive," situations can arise in which we, and those dear to us, can be maimed or killed under circumstances entirely beyond our control. The only control we have is to stay at home. Yet, while thousands are killed and maimed on our highways, few of us refrain from driving automobiles or riding in automobiles because of this terrible accident toll. We have weighed the hazard against the good and made our decision.

If a man doesn't care to accept the exposure to radiation incidental to employment in an atomic energy plant when all of the necessary precautions have been provided and his radiation exposure is no more than the maximum permissible level, there is only one thing for him to do. He should find other work, the hazards of which he is willing to accept.

The safety record of the atomic energy program is phenomenally good. Over a 15-year period, with thousands of people engaged in extremely dangerous operations, including vast construction projects carried on with tremendous speed, the overall safety record compares with the best of American industry. The fatal accident record is less than half of that of the best of American industry. Although 200 people have been killed in the program, only 3 were in accidents involving radiation. The others were killed in what we sometimes call "normal" industrial accidents—fires, falls, electrocutions, motor vehicle accidents, and the like.

The effects of excessive radiation exposure on the body are manifested in several ways.

Radiation Sickness

This is a sickness produced by a massive overdose of penetrating external radiation, and it causes nausea, vomiting, diarrhea, malaise, infection, hemorrhage, and, of course, if serious enough, can cause death.

Radiation Injury

Radiation injury consists of localized injurious effects, generally from overdoses of less penetrating external radiation and most often to the hands because contact is usually with the hands. This can cause burns, also loss of hair, and skin lesions. Genetic damage is also a form of radiation injury.

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Radioactive Poisoning

Radioactive poisoning is illness resulting when dangerous amounts of certain types of radioactive materials enter the body, causing such diseases as anemia and cancer.

When we look at the foregoing, we realize that we can get into trouble with radiation by two entirely different means. One, by radiation originating from a source outside the body and coming at the body from the outside; the other by exposure resulting from radioactive materials which have been taken into the body. It is almost obvious to us that precautions against one type of hazard will not be particularly helpful in protecting against the other type of hazard, and that, in fact, the radiation problem is made up of two separate problems.

This is indeed the case. As a matter of fact, certain radioactive materials are no hazard at all outside the body. However, if we got the same materials inside the body in sufficient quantity, we could have a case of radioactive poisoning.

Therefore, it is fundamental to our understanding to realize that the radiation problem is not one problem, but two problems, the problem of external radiation, and the problem of internal radioactive poisoning. The precautions that we take in various exposures to radiation hazards depend upon which hazard is present. Of course, in a given situation, we may have both types of hazards. See figure 3.

To make our study easier, we will stick to the subject of external radiation hazards entirely for the next part of our discussion. When we have completed this subject, we will then take up the problem of the internal radiation hazard. Along the way, we may learn a little about the nature of radiation itself, but our prime interest is in learning how to live with the hazard.

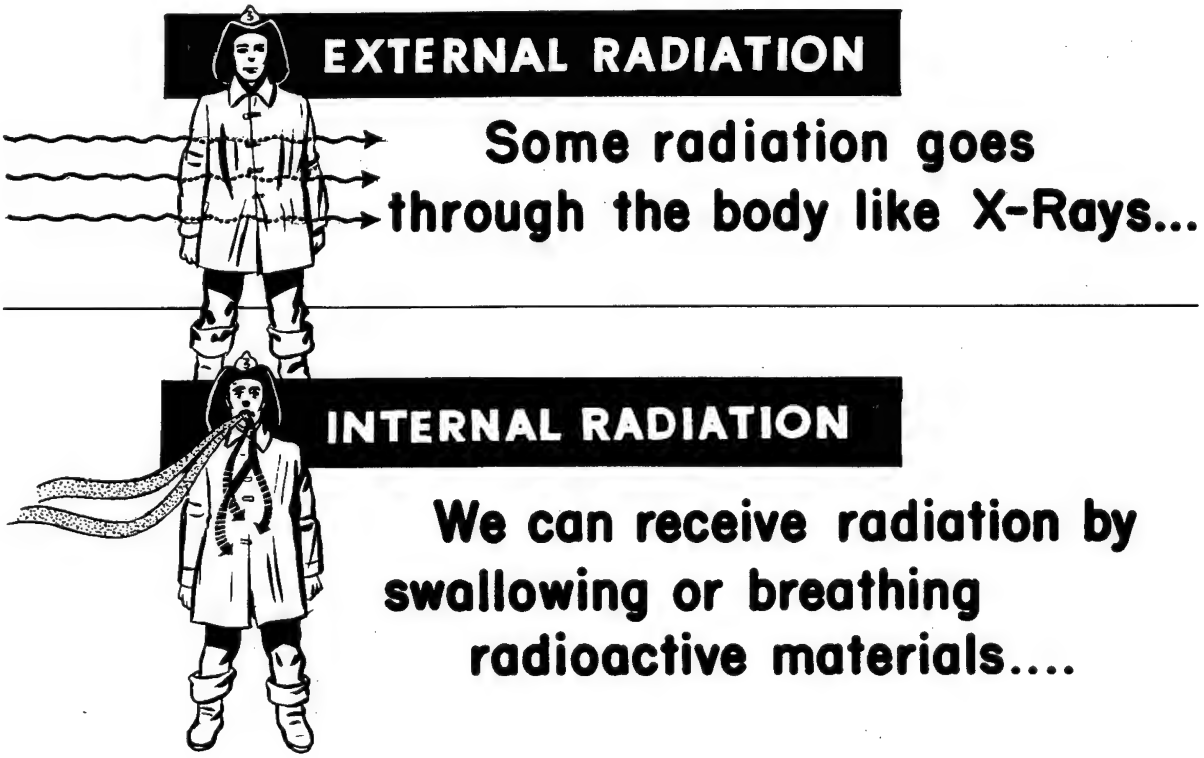

FIGURE 3

Chapter IV

EXTERNAL RADIATION PROBLEM

The external radiation hazard comes in two forms:

1. Long-range, highly penetrating external radiation.

2. Short-range, less penetrating external radiation.

We will consider the long-range, highly penetrating external radiation first.

We are talking about a type of radiation similar to X-rays, consisting of pure energy with no mass. These rays originate from some radioactive materials outside the body, and come at the body like a shower of arrows or a beam of light. In order to simplify our problem, let us think of one ray at a time. Each ray is a bundle of energy. It penetrates the body to some depth or other before it does its damage and the energy of the ray is spent. (The effect of radiation on the body is, of course, a little more complex than this, but this concept will admirably serve our purpose.)

Observe the figure of the man in figure 4. The rays come at him from the radioactive source which is giving off the penetrating radiation. Each one of the rays penetrates to a different depth in the body before it finds its target and has its effect on the structure of the body. Also note that a sizable proportion of the radiation passes through the man's body without ever touching him. (These rays do him no harm.)

At first glance this may seem strange. For instance, most of us would agree that light rays cannot pass through a man's body without touching him, but if we place our fingers over the lens of a strong flashlight, some light comes through our fingers. If we stop and think for a bit, we realize that if it were not for the fact that some radiation can pass through the body without touching it, we could hardly take X-ray pictures. The X-ray machine is pointed at the patient's back, the film is placed at his chest. If his body stopped all

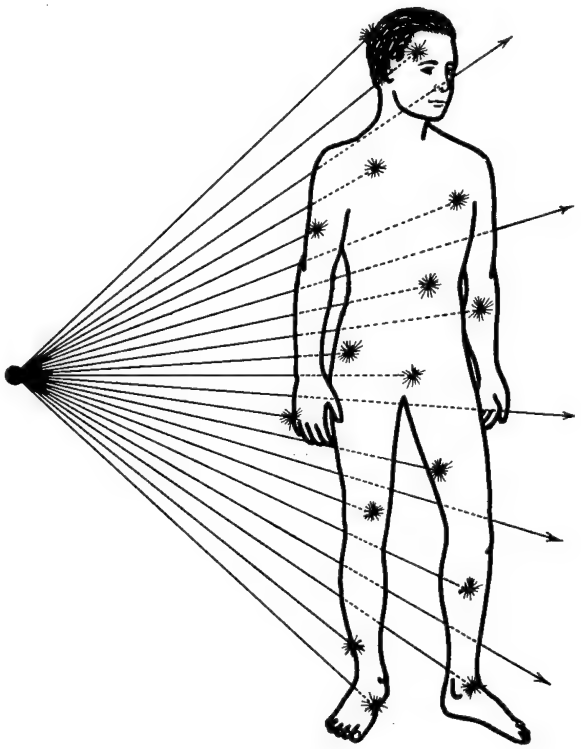

FIGURE 4

of the radiation, there would be no radiation left to reach the film. It is obvious that some of the radiation gets through to the film.

Figure 5 is a concept of what water might look like if we could magnify it with a microscope tremendously more powerful than any in existence.

Most of us know that water is H_2O. This means that the water molecule consists of an atom of oxygen with two atoms of hydrogen

tied onto it. Each one of the figures in our illustration represents a molecule of water. Atoms consist of two parts, a heavy dense core called the nucleus, which contains practically all of the weight, and very tiny particles called electrons that spin around the nucleus like the planets around the sun.

The trouble with our illustration is that it is not at all to scale. If the nuclei of our atoms were actually as big as we have shown, the electrons would be many hundred feet away.

We see that if the electrons are this far away from the nucleus that the nuclei of the various atoms must be relatively quite far apart. This is the case. Yet, when we feel a substance, when we step on the scale, what we are feeling or what we are weighing is the sum total of the nuclei, these little incredibly heavy balls of matter spinning around in mostly empty space. These nuclei are so heavy that if a child's marble could be made of this material only, it would weigh 37 million tons.

Therefore, we see how it is possible for the ray to penetrate quite a distance into the substance before it hits anything.

The rays from radioactive materials do not hit the nucleus in significant amounts; few of them have enough energy to penetrate to this hard ball of matter. They do hit the electrons, which are spinning around the nucleus, and the energy of the ray is spent. The damage done by the rays from radioactive materials is practically all done by this knocking the electrons out of the atom, and if enough electrons are knocked out of enough atoms, we have radiation damage. We should, of course, have some appreciation of the numbers involved. For instance, there are 6 sextillion atoms

6,000,000,000,000,000,000,000

in a single drop of water.

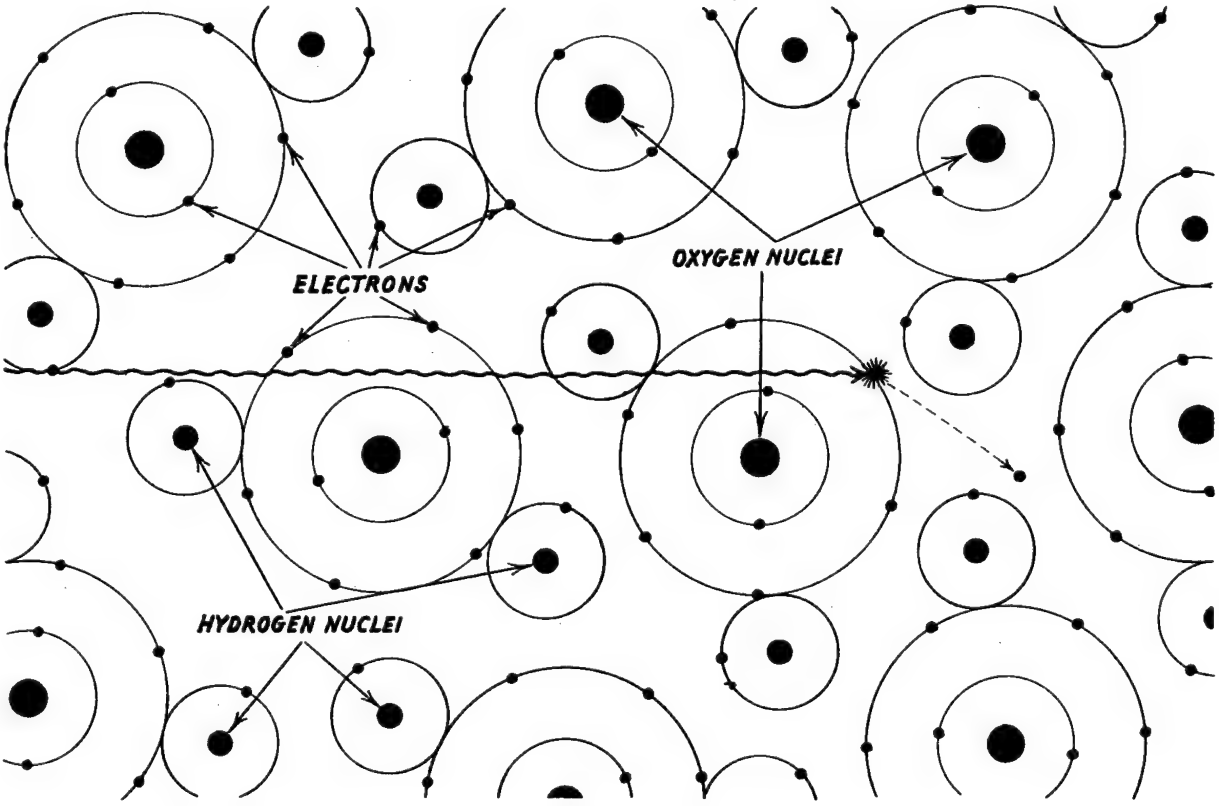

FIGURE 5

It is a hard thing to discard our concept of things being solid and accept this new concept that matter is mostly empty space, but it is essential if we are going to understand this radiation business. So let us try another approach.

Consider a series of rows of air-jets, perhaps 20 rows of jets with 20 jets in a row, making a total of 400 air-jets in a square. The various jets are staggered within the square. On each air-jet a ping-pong ball is balanced. This ping-pong ball goes up and down as the air-jets are turned on and off at random. If we stand close to this setup, we will see the individual ping-pong balls. If we move away 300 feet, we will not see the individual balls, but what would appear to be a solid white mass. However, just because this appears to be a mass, we know that this does not make it a mass.

The fact that matter *appears* to be solid, we now know, does not prove this to be true. All matter consists of little hard balls of material linked together by trading and sharing electrons floating around in what is mostly empty space. It is quite easy for the rays to penetrate various depths before they find an electron to hit. If we were to fire a rifle at our "solid" white target from 300 feet, we know that it would be impossible to say in which row we would get a hit on the ping-pong ball. As a matter of fact, it would be quite possible for the bullet to pass through the ping-pong balls without doing any damage at all.

If we substitute a machine gun for our rifle and consider that the bullet would disintegrate upon hitting one ball, it is easy to understand that while our hits would be scattered, we would get more hits in the front rows, and few hits in the back rows. If we carried on enough experiments we could arrive at tables giving us the percentage of hits to be expected in each row.

For penetrating external radiation, such tables are available to the radiologist. They are called dose depth distribution tables, but we need not get that technical.

This radiation effect is going on in our bodies constantly. We are constantly being bombarded by cosmic rays from outer space and rays originating from radioactive materials in the structure of our buildings, in our bodies, in the food we eat, etc. When an electron is knocked off an atom, the cell of which the atom is a part is damaged. The body's repair mechanism swings into action to repair the damaged cell. Perhaps this constant bombardment from natural background is doing us some harm, or, possibly, some good. Nobody knows one way or the other for sure. In any event, we have been able to live with it and adapted to it for many, many thousands of generations.

On the other end of the scale, we know that excessive radiation exposure can bring about sufficient damage to cause death.

Our problem is to regulate our radiation exposure to the amount from which there will be no apparent effect. There is no single answer to the question, "How harmful is radiation exposure?"

A simple illustration helps to prove this point. Slap your hand on the desk, smartly enough to make it sting. There is no visible damage, but I am sure that you will agree that possibly some cells in the palm of your hand have, in fact, been damaged by this blow. If you strike your hand somewhat harder on the desk, visible damage in the form of black and blue marks will show up. The body will generally recover from this damage after some effort on the part of the body repair system to rebuild the damage, and there will be no apparent aftereffect. A harder blow would cause broken bones which would not heal properly unless given adequate medical attention. The severest degree of damage, of course, would be to break the hand off at the wrist, because this damage would be irreparable.

Just as there is no simple answer to the question of how harmful it is to slap your hand on the desk, there is, likewise, no simple single answer to the question of "How harmful is radiation exposure?"

The Roentgen

We have seen that, on the one hand, it is possible to have radiation exposure so small that it has no apparent effect, and on the other hand, it is possible to receive sufficient radiation exposure to cause death. It is, therefore, necessary that we have some unit of measurement with which to measure radiation exposure so that we can determine what the acceptable limits are and be sure that we are operating within those limits.

The unit of measurement for penetrating external radiation exposure is the roentgen (the milliroentgen is 1/1000 of a roentgen). It is an arbitrary unit of measurement. Its exact definition is of significance only to experts. Our interest lies in how many roentgens are too many.

Single Exposures

It is impossible to say how many roentgens it will take to kill any specific individual because we all vary in our resistance to any attack upon the body, whether it is by radiation, electricity, poison, injury, diseases, etc. It is quite certain, however, that no human being could survive 1,000 roentgens of *total body* radiation delivered in a *short* space of *time.*

Both of these conditions are most important. The effect of 1,000 roentgens of radiation delivered to the total body is by no means the same thing as 1,000 roentgens delivered to a small portion of the body any more than a third degree burn of the palm of the hand is the same thing as a third degree burn of a large area of the body.

Similarly, the short space of time is an important part of the definition. The short space of time is defined as 24 hours, or less. The ability of the body to withstand any insult is, of course, increased if the same amount of insult given to the body is spread out over a longer period of time. Whiskey can be poison, but many people, apparently without any demonstrable injury, can drink an ounce of whiskey each evening before dinner over an extended period of time. If, however, a person attempts to consume a three month's quota of whiskey in one sitting, he will probably die of alcoholic poisoning because the body has not been given sufficient time to recover from the poison.

The dose it takes to kill one specific individual is not a good measure of the fatal dose to others because of individual differences. The term that is used in this field is the so-called median lethal dose, or LD/50. This is the dose that it takes to kill 50 percent of the subjects. The LD/50 for penetrating external radiation is about 500 roentgens delivered to the *total* body in a *short* space of time (24 hours or less).

This means that if a representative sample of the population were subjected to 500 roentgens of total body radiation within a 24-hour period, approximately 50 percent of these people would die, and the other 50 percent would recover.

At about 200 or 250 roentgens of total body radiation in a short space of time, we would expect to find the first death.

From 100 to 200 roentgens of total body radiation in a short space of time, we would expect nausea, fatigue, vomiting, and sickness, but no fatalities.

At about 50 roentgens of total body radiation in a short space of time, we would get some slight temporary blood changes which would reverse themselves with the passage of time. The person would have no symptoms which he himself would notice.

At 25 roentgens of total body radiation in a short space of time, we would probably find no detectable effect.

Figure 6 illustrates these levels.

Remember that all of these figures are on the basis of total body radiation within a short space of time. We should also note that it is quite difficult for a person to receive high radiation exposure unless there is gross violation of simple safety precautions.

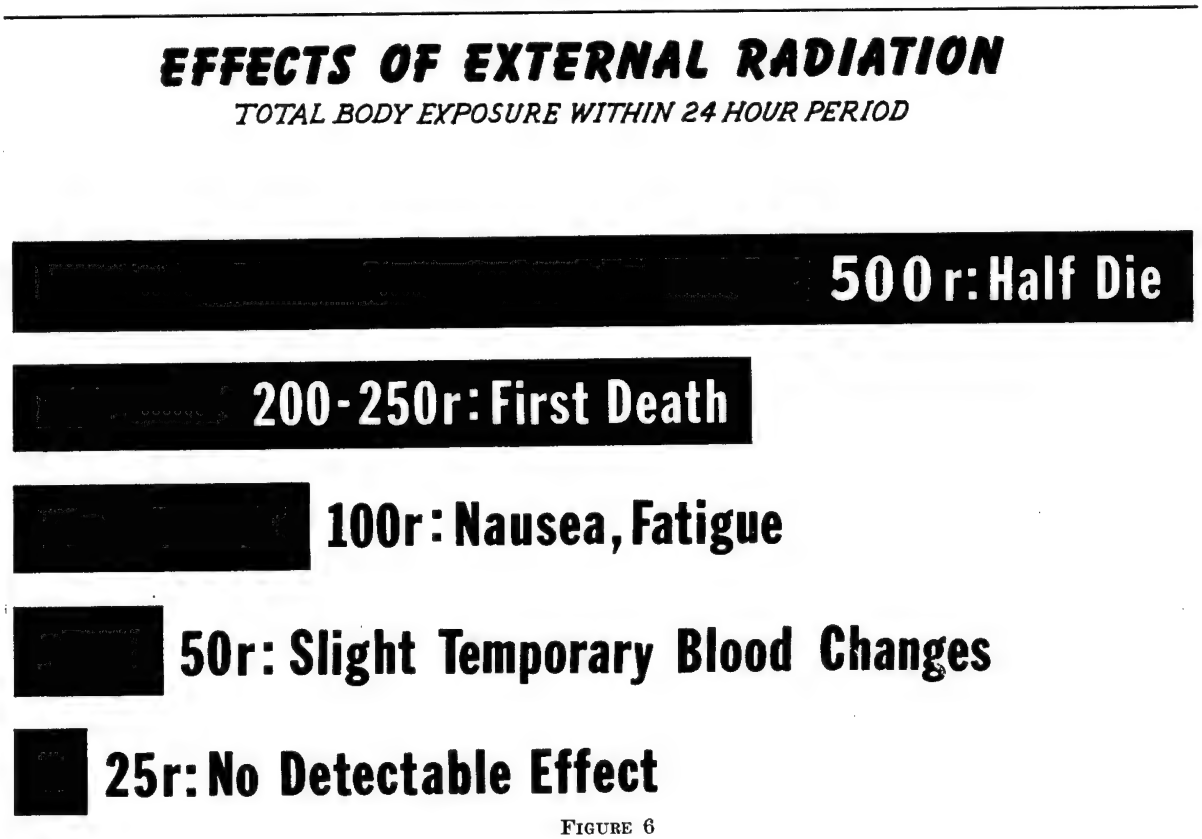

FIGURE 6

Continuous Exposures

Thus far, we have been thinking about a single incident of radiation exposure, one from which the man dies, gets sick and recovers, or receives no apparent effect at all; the sort of problem that is very similar to the ordinary injury situation. A man gets up on a rickety ladder, the ladder breaks, and he falls. He can die, he can be injured and recover, possibly with some permanent disability, or he may be fortunate and have no ill effects at all. In any case, the incident is closed, the effect on the body is accomplished, and that is pretty much the end of it.

There is another possibility with radiation, however—the problem of repeated small exposures to radiation over an extended period of time. What are the effects of this on the individual and what sort of radiation safety levels must we have so that there will be no apparent effect and so that the hazard will be consistent with the other hazards of industry as we know them?

To how much radiation can people be safely exposed? How can we maintain the radiation hazard consistent with the other hazards of human endeavor?

There are two considerations which we must take into account. The first is the effect of the radiation on the individual himself. That is to say, what damage is done to the *individual* by repeated small dosages of radiation over a period which might conceivably extend from the time that he enters industrial employment until he retires, perhaps as much as 50 years later?

The other problem with respect to *society* is the so-called genetic effect—the problem of damage done to the genetic life stream of the population by the exposure of large numbers of individuals to ionizing radiation.

Complicating the whole situation are the facts that all of us receive background radia-

tion from cosmic rays and naturally occurring radioactivity, that we are all exposed to a certain average level of radiation from medical and dental X-ray procedures, and that we all get a small increase in our background exposure from fallout from atomic weapons tests, no matter by whom conducted. The figures presently used for the regulation of radiation exposure in the individual take all of these factors into account.

In so far as the direct effect on the individual is concerned, it appears that *high* dosages of radiation received over a relatively short time can have some effect on the life span of the individual. The National Academy of Sciences, National Research Council Report cites studies of a group of radiologists, some of whom received as much as 1,000 roentgens of X-ray exposure, which show, on the average, a life span 5 years shorter than that of other physicians. There is, as yet, no conclusive evidence that low dosages spread over a period of years have any life-shortening effect. On the other hand, there is no evidence to indicate that there is a level of radiation exposure below which we can say there is no life-shortening effect at all.

Radiation, of course, is not the only factor in causing shortening of life. We have only to review in our minds the interviews traditionally conducted by the press with those who have reached an advanced age, in which these persons are asked to what they attribute their long life. The answers collectively cover the entire gamut from those things which many of us believe to be deleterious to things which most of us believe to be beneficial. Would you, for instance, say that the widespread use of the automobile causes a longer or a shorter life span in the average individual? Much heat and very little light could be generated in an argument on this subject.

Genetic Effects

The genetic effect of radiation is one of the areas in which the laymen is most completely confused. We should first dispose of some common misconceptions. There is no relationship between the so-called genetic effect and sterility or impotence. Radiation doses so high as to be nearly fatal can bring about sterility, which is the inability to conceive children despite normal sexual relations. Impotence is the inability to carry on sexual relations and radiation has no effect on this.

Another misconception is the idea that all congenital (present at birth) handicaps are genetic. Only about half the recognizable congenital handicaps are genetic in origin; the others are caused by disease or other factors.

The next misconception that we should clear away is the idea that there is any direct relationship between an exposure to radiation and the conception and birth of a defective child in any specific instance. It is true that radiation striking genetic material which is used in the conception of the next generation may cause a mutant which may show up in a future generation. However, we cannot determine the cause of any specific mutant. The mutant may, or may not, be caused by radiation, but even if caused by radiation, we cannot know the source of the ray. On the other hand, no measurable amount of radiation from any source is so small that we can say positively it cannot have a genetic effect. The geneticist necessarily is concerned not about individuals but about the population as a whole.

The problem, therefore, is not one of protecting a specific individual but of protecting the entire population by keeping all exposure to radiation down to the lowest practical limits.

The portion of the population of primary interest to the geneticist is that portion which has yet to make its substantial contribution to the next generation. He is, therefore, interested primarily in the radiation exposure of individuals from the time of conception to the age of 30, because by the age of 30, we have made half of our contribution to the next generation. By the age of 40, we have made 90 percent of our contribution to the next generation. The effect of radiation damage on

genetic material is different than the effect of radiation damage on ordinary cell material. When genetic material is damaged, a pattern is damaged. Once a pattern is damaged, it remains damaged. Thus, it is possible that genetic material damaged by a radiation exposure in a person's early childhood may have its effect in a child conceived by this person many years later. However, we must also bear in mind the fact that the only radiation exposure which is genetically significant is that which strikes the reproductive organs. Radiation exposure of other organs or other parts of the body has no genetic effect whatsoever.

Permissible Rate of Exposure

With all the foregoing taken into account, the supplement to Bureau of Standards Handbook #59 sets the permissible rate of radiation exposure to industrial employees at an average of 5 rem per year for each year after the age of 18. This is illustrated in figure 7. Note that the effect is to keep down not only the total amount of radiation exposure permitted to an individual in his lifetime but to keep down the rate at which it accumulates, so that his exposure does not exceed 60 rem at the age of 30 and 110 rem at the age of 40.

A roentgen measures penetrating external radiation only, *in the air*. The rem is a measure of the effect of radiation in the body and is used for all types of radiation. At this point all we need to know is that one roentgen of exposure to penetrating external radiation equals one rem of effect in the body.

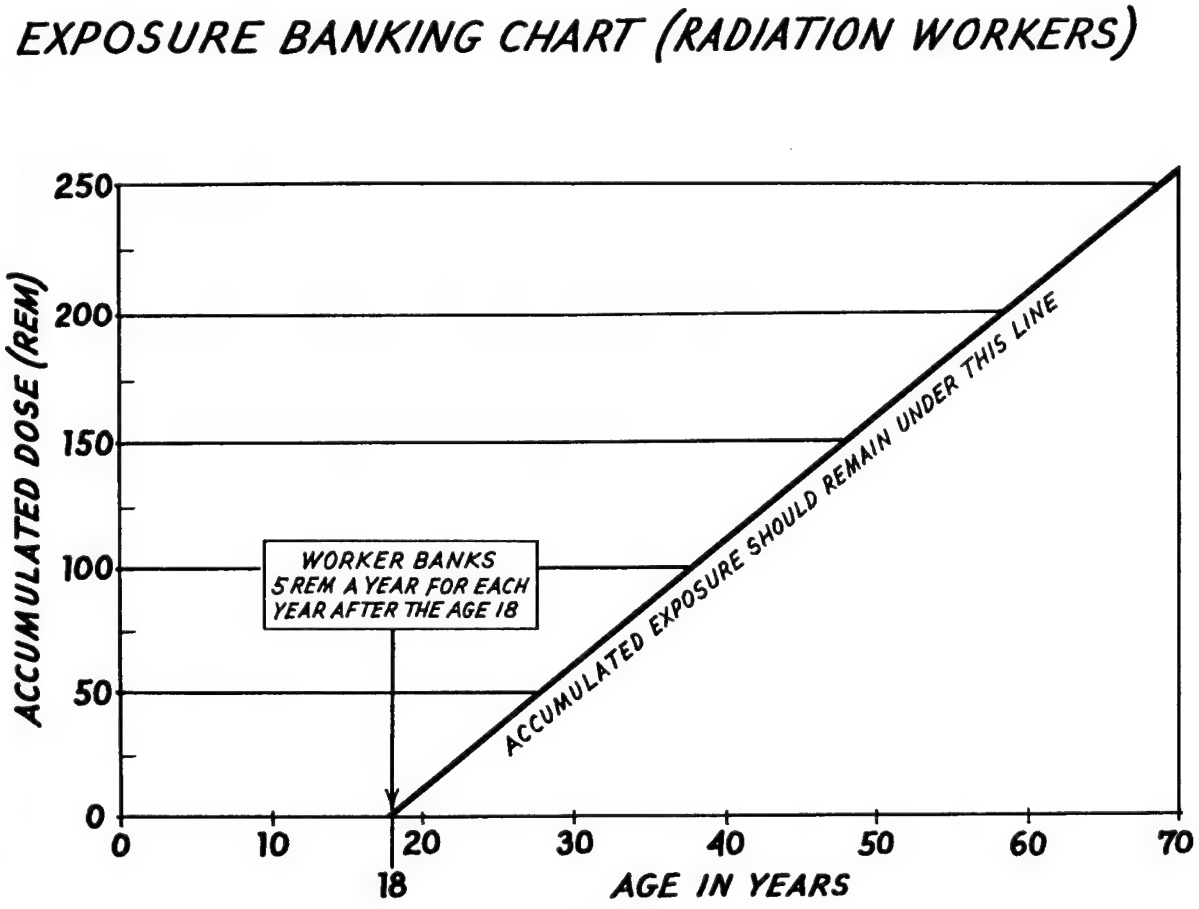

FIGURE 7

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An individual can receive radiation exposure in any given year up to 12 rem.

The easiest working concept to consider is that the man has a radiation bank account. Into his account 5 rem are deposited per year for each year after age 18. He can draw on this at the rate of 12 rem per year. If he overdraws his account slightly, no particular harm is done, but in order to keep down his exposure, he is restricted until, by the passage of time, his exposure is down to, or below, the permitted line.

Let us consider a man who enters radiation work at the age of 23. Five years have passed since his 18th birthday.

Please note carefully that this illustration is used just to demonstrate the working of the radiation banking concept. The average annual exposure of all monitored employees in AEC plants is less than $\frac{1}{10}$th rem per year, and the 9-year average of the *highest* annual exposure from all plants is 5.1 rem.

5 year x 5 rem per year	=25 rem in bank.
1st year of work, used	−12 rem used.
	13
Added to bank by passage of 1 year	+5 rem
	18 rem balance, end 1st year.
2d year of work, used	−12 rem used.
	6
Added to bank by passage of 1 year	+5 rem.
	11 rem balance, end 2d year.
3d year of work, used	−10 rem used.
	1
Added to bank by passage of 1 year	+5
	6 rem balance, end 3 year.
4th year of work used	−12 rem used.
	−6
Added to bank by passage of 1 year	+5
	−1 balance, end 4th year (overdrawn).
Exposure during 5th year	−4 rem.
	−5
Added to bank by passage of 1 year	+5
	0 rem balance.

In any regulations, specific numbers must be used, and an individual may feel that he has been injured if the specific number cited has been exceeded to any degree at all. The purpose of the regulation is to keep down the radiation exposure of everyone, including that portion of the population engaged in atomic energy work. The fact that a given individual on a given occasion gets a dose slightly in excess of the figure given by the regulations should not be a cause of concern to the individual. He has not been injured, but, of course, it is of serious concern to see that the circumstances which brought about this technical overexposure are changed so that the situation will not continue into the future.

The situation is somewhat similar to speed limits on the highway. We all know that from the practical point of view there is no real safety difference between driving at 62 or 60 miles per hour. Yet, when the speed limit is posted at 60, the police officer is doing his duty when he arrests us for exceeding the limit by any margin, no matter how small. The point is that in regulating any activity, we must state specific numbers in order to have a definite point of reference. The effect of exceeding the limit slightly, however, is rarely of practical significance.

It is particularly important that we understand this in radiation work because, for administrative purposes, the permissible amount of radiation exposure is broken down into quarterly and weekly periods of exposure. Sometimes there is a feeling that if a man has received his weekly permissible exposure, he is literally standing on the brink of disaster, and any further exposure to radiation may cause him severe harm. For instance, concern has been expressed over the possibility of an employee who had received his weekly permissible dose being involved in an automobile accident. The supposition was that by adding X-ray exposure to the permitted exposure, "the doctor would be unwittingly guilty of homicide." Nothing could be further from the truth.

The very intensive efforts made by radiation safety personnel to keep down radiation exposure may bring about a wrong conclusion in the minds of the employees. The 12 rem per year is broken down into 3 rem per quarter. Under the regulations, it is permissible for the employee to get his 3 rem in any manner during the quarter. That is to say, he may get a single short exposure which amounts to 3 rem (3,000 millirems), or, as is more generally the case, particularly when work is going on with radioactive materials constantly, the 3,000 millirems may be divided up among the 13 weeks in the quarter. Thus, for instance, a limit of 100, 200 or 250 millirems per week may be administratively set, in order to keep down the radiation exposure of the individual so that he does not exceed the 3 rem per quarter.

For this reason, if an employee should exceed the administratively set permissible exposure, there may be quite an investigation of exactly how this came about. The reason for the investigation is not necessarily because specific injury has been done to the employee but the fact that exceeding the level indicates that some unplanned radiation exposure occurred. The concern is not so much with the specific incident which occurred but the fact that such an incident indicates a possible breakdown in procedure which might cause trouble if allowed to continue.

Detailed regulations for permissible radiation exposures in AEC contractor activities are found in the AEC Manual. Regulations for licensee exposures are found in Title 10, Part 20 of the Code of Federal Regulations.

It should be further noticed that the National Committee on Radiation Protection Recommendations, contained in Bureau of Standards Handbook 59, permit a single, once-in-a-lifetime 25-rem emergency exposure without effect on the 5-rem per year exposure rate. Medical and dental X-ray procedures were taken into account when the regulations were set. The regulations also permit higher exposure levels to the hands than to the body as a whole.

We see, therefore, that the radiation exposure figures have been set far below the level at which an injury can occur in any specific exposure situation. They are set up at this low level to reduce the cumulative effect of the radiation exposure, primarily because of the possible genetic effect of exposure up to the age of 40; secondarily, because of possible effects on the individual as a result of continual low level exposure to radiation.

The levels have been set in the light of our best available knowledge, as have other permissible exposure levels, such as for carbon tetrachloride, carbon monoxide, or other industrial poisons. Further research may tell us

that radiation levels presently permitted should be reduced because of various factors not yet discovered. On the other hand, it is possible that further research may permit a relaxation of the rule.

Regardless of the numerical values of radiation exposure permitted, the *means* of protection against radiation hazards will not change. The *degree* to which we apply the means of protection will, of course, vary, depending upon the level of radiation exposure we intend to permit.

Chapter V

PROTECTION FROM EXTERNAL RADIATION

The means of protection from external radiation exposure are a combination of three things: *Time*, *distance*, *shielding*.

That is to say, protection is provided by:

1. Controlling the length of time of exposure.
2. Controlling the distance between the man and the source of the radiation.
3. Placing an absorbing material between the man and the source of the radiation.

We cannot use just one of the factors of protection. The factor of time is always involved, but we may have time in combination with distance, shielding, or both. In order to understand each of these factors, we will discuss them separately.

Time

The effect of *time* on radiation exposure is easy to understand. If we are in an area where the radiation level from penetrating external radiation is 100 milliroentgens per hour, then in 1 hour we would get 100 millirems of exposure. If we stayed 2 hours we would get 200 millirems; if we stayed 4 hours we would get 400 millirems; and if we stayed 8 hours we would get 800 millirems of exposure, as shown in figure 8.

Time is used as a safety factor by keeping the time of exposure down to the absolute minimum. For instance, if work must be done in a high radiation area, the work to be done should be carefully preplanned outside the hazard area so that the minimum time is used within the radiation area to accomplish the work.

Time is also used sometimes for administrative regulation. Consider a situation where there is but a single radiation source in a plant. This source is in a room in which the radiation level is about 20 mr per hour. We don't want anyone to get more than 100 mr per week. If we wish our employees to be able to go into the room in which this radiation source is located on each of the 5 days of their work week, we would divide up the 100 mr per week by 5 days and arrive at an administrative permissible dose of 20 mr per day.

Since the rate is 20 mr per hour, we would then post a sign that no employee was to remain in this room more than 1 hour in any day. By this means, we would anticipate that his radiation exposure would not exceed the limit set for this operation. By the use of film badges, or dosimeters, which will be discussed later, we would check his actual radiation exposure.

Time is also useful to us in other problems. In an accident on the highway, for instance, a relatively high radiation area may be created because a high intensity source of penetrating external radiation is stripped of its shielding as a result of the accident.

On the opposite side of a wide highway, such as a turnpike, there might be a radiation level quite high when considered in terms of permissible radiation level in industrial plants. Assume that the radiation level on the opposite side of the highway from the accident, is 5 R per hour. This is a very high radiation level when considered in terms of normal industrial exposures. However, assume that it would take a person riding in a car only 10 seconds to get through the radiation area. There are 3,600 seconds in an hour. Therefore, the person driving through the area would receive only $\frac{1}{360}$th of the 5 r per hour (5,000 milliroentgens per hour) rate. The actual dose to a person passing through that

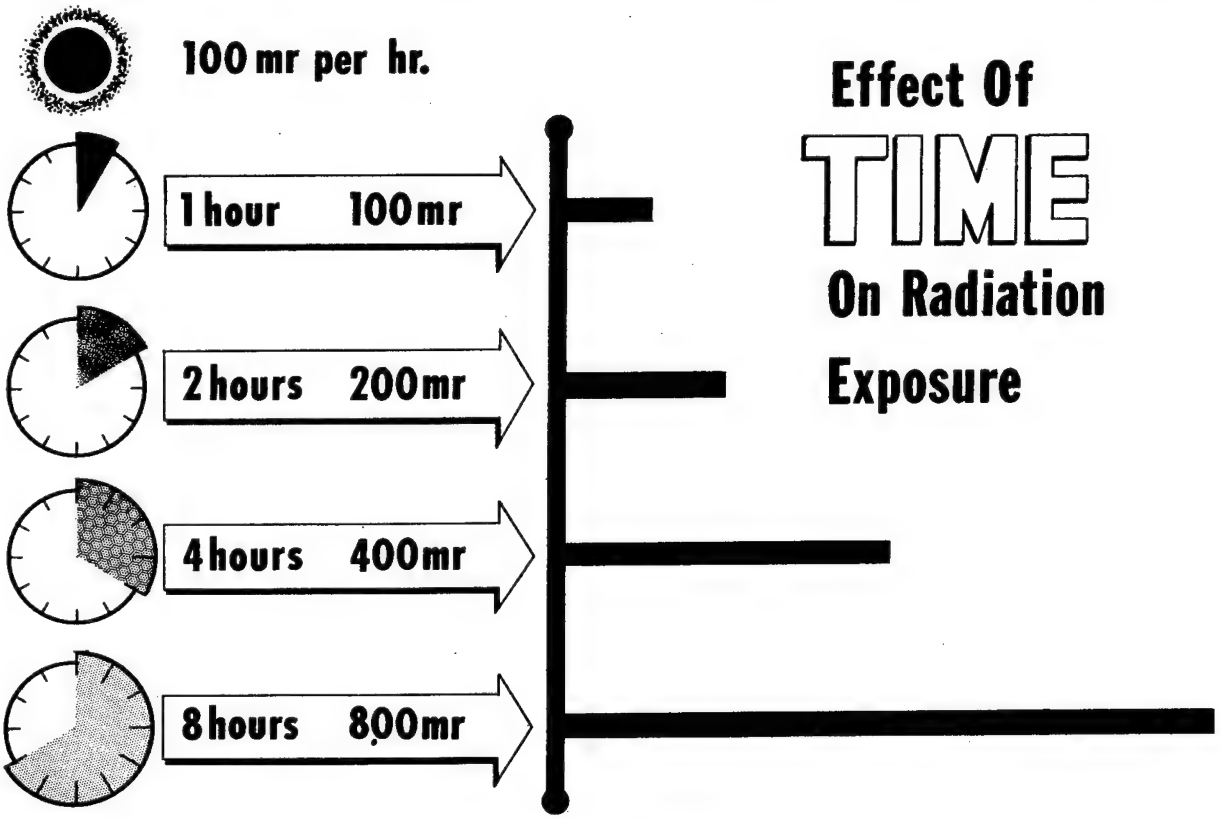

FIGURE 8

area and remaining only 10 seconds would be about 14 mr, an inconsequential dose of radiation.

Distance

The effective of *distance* on radiation exposure is quite startling. This effect is due to the inverse square law. That is to say, the intensity of radiation falls off by the square of the distance from the source. Figure 9 shows it very simply.

If we had a *point* source of radiation giving us 1,000 units of penetrating external radiation at 1 foot, we would receive only 250 units at 2 feet because we have doubled the distance, and the effect on the radiation level is to reduce it to $(\frac{1}{2})^2$ or $\frac{1}{4}$. When we have tripled the distance, we have reduced the dose to $(\frac{1}{3})^2$ or $\frac{1}{9}$th, to 111 units and so on. At 10 feet away, we have $(\frac{1}{10})^2$ or $\frac{1}{100}$th of the radiation exposure at 1 foot, i.e., 10 units.

We should explain that the inverse square law applies to the degree that distances are large in relation to the size of the source. Radiation sources used in industry for penetrating radiation are generally quite small in size, so the inverse square law can be applied to distance in the immediate vicinity of the source. If, however, the source is large in size, such as the side of a reactor, which covers a considerable area, or as might be the case if the radioactive material were dispersed, then the inverse square law does not start to apply until the distances are large in relation to the size of the source.

Let us look at our chart now in terms of actual doses and their possible effect on a man. Consider that the radiation rate at 1 foot is 1,000 r per hour and a man remains at that

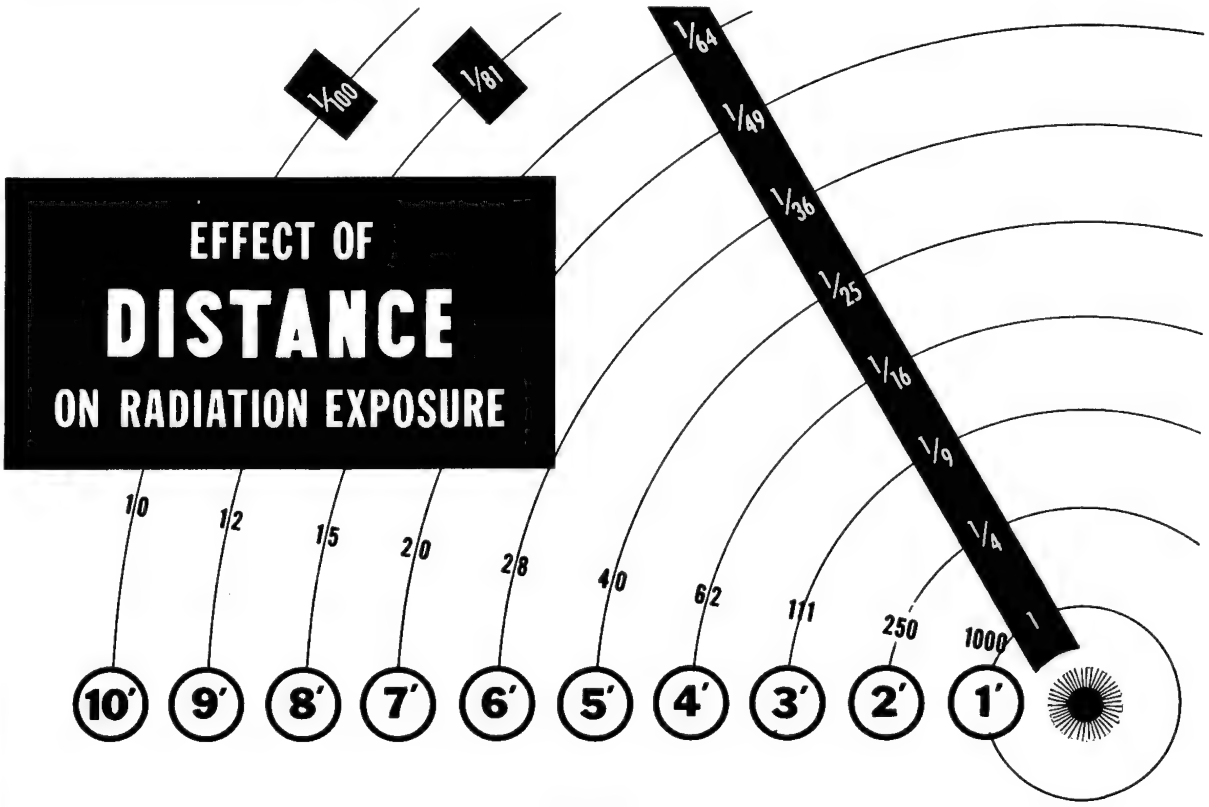

FIGURE 9

distance for 1 hour. He will receive 1,000 rem, an absolutely lethal dose of radiation.

If he remains 2 feet from the source for 1 hour, he will receive 250 rem. This puts him on the threshold of dying and he might be extremely ill. At 3 feet, he would receive only 111 rem, and we would not expect that he would die, but he might be quite sick for a period of time.

At 4 feet, he is already in a range where there would probably be no symptoms that he would detect, and the only damage that we could find would be certain changes in his blood which would reverse themselves with the passage of time. If we extended our chart out to 20 feet, we would see that the man would get only 2½ rem, this is $\frac{1}{400}$th $(\frac{1}{20})^2$ of the dose at 1 foot, less than the amount permitted to a radiation worker in a 3-month period.

We see, therefore, that there is a dramatic fall-off in the rate of radiation exposure as we go away from the source of the radiation, and a very little bit of distance can go a long way in increasing our safety factor.

Conversely, as we close in on the radiation source, our levels will go higher by the same mathematical process. For instance, if we move in to 6 inches, the radiation rate will go from 1,000 r per hour to 4,000 r per hour. This helps to make us realize one of the most fundamental rules of radiation protection, which is to maintain the maximum possible distance between ourselves and the source of the radiation. We should avoid touching materials which give off significant amounts of penetrating external radiation because in such a case we have obviously no distance at all working for us.

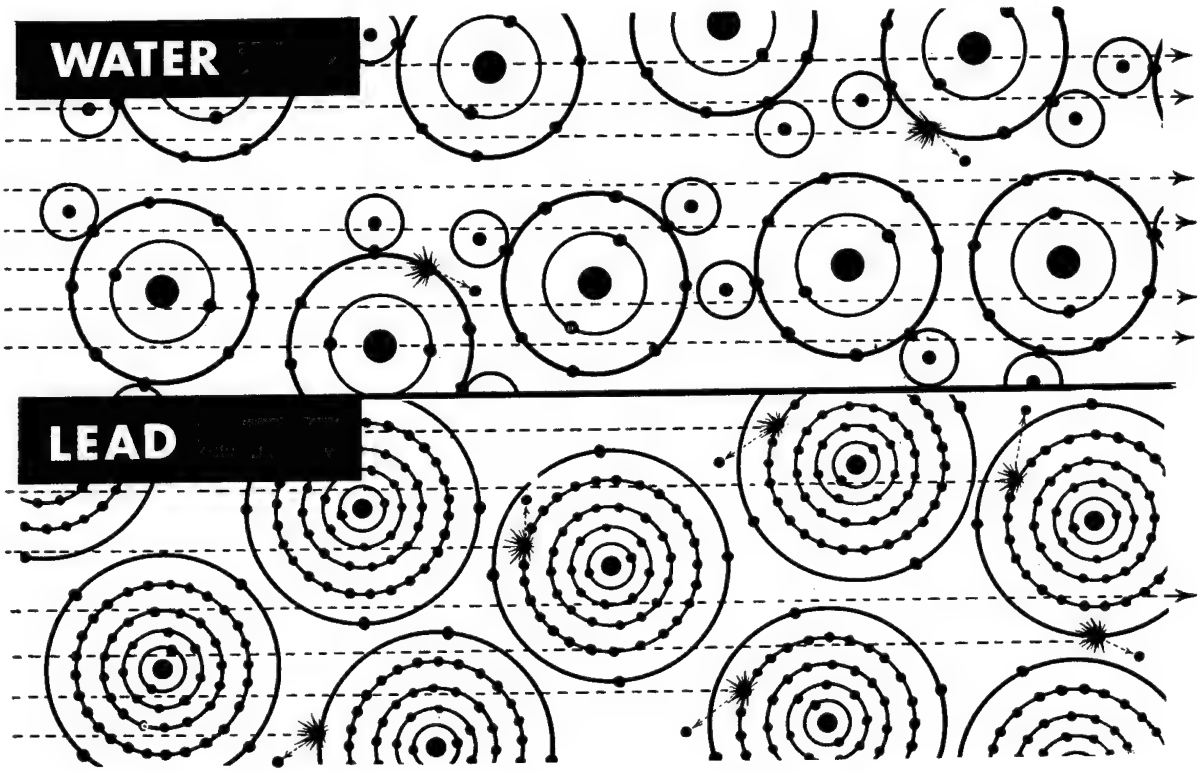

FIGURE 10

Shielding

You will recall that we said that the damaging effects of radiation comes from the fact that the rays strike electrons in the body and knock them out of their orbit, and if this happens to sufficient electrons in the body, we have received radiation damage. If we wish to stop a high proportion of the rays before they get to us, we can place between ourselves and the source of the radiation a material which has a lot of electrons in its makeup. The more electrons there are in the makeup of the material the more of the radiation will be stopped.

Figure 10 shows lead and water in a rough comparison of their atomic makeup. Notice that lead has a lot more electrons in the orbits of each atom than does water. Therefore, lead makes a better shield than water.

Figure 12 shows the relative efficiency of various shielding materials. Lead, iron, concrete, and water, are efficient in about the proportions shown on the chart in stopping the same amount of radiation. Various shielding materials are used in various applications, depending upon the purpose to be served. Lead, for instance, is quite compact and is most suitable where space requirements are a factor. On the other hand, water is used where it is necessary to see through the shielding material and to work through it with a long-handled tool to perform necessary operations, such as, sawing or cutting the radioactive materials.

When we consider that matter is mostly empty space, we realize that no material can be an absolute barrier to radiation. Regardless of the thickness of the material, we can see how some radiation can get through the

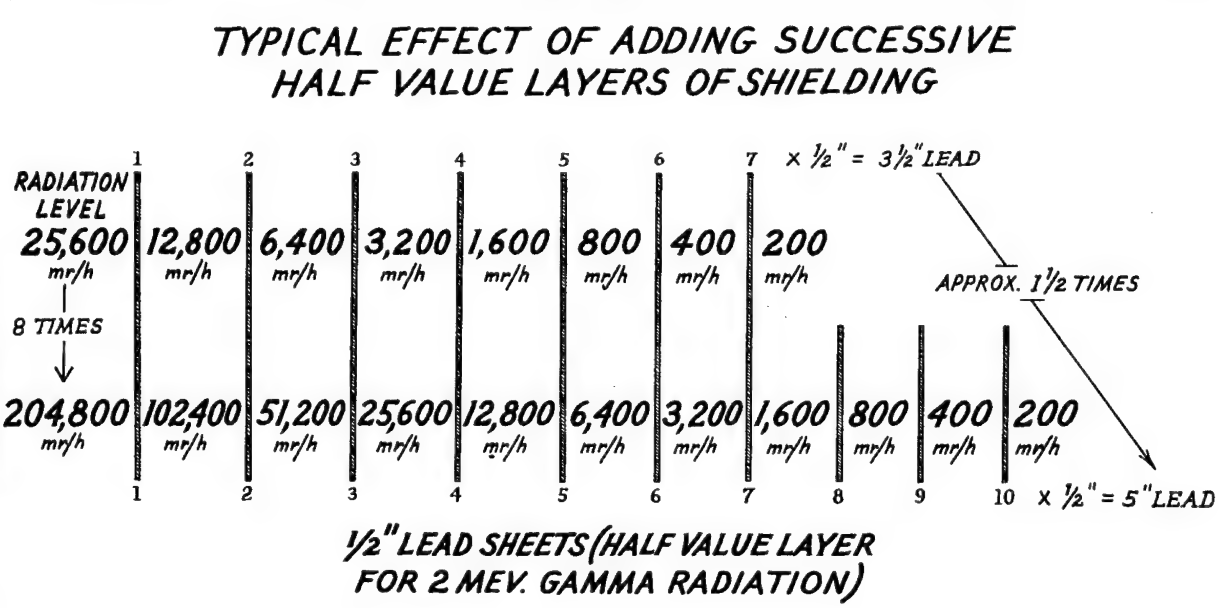

FIGURE 11

material without hitting any electrons and, therefore, without being absorbed.

Half Value Layer

In calculating shielding for external radiation exposure, the amount of shielding it will take to stop *all* of the radiation is not a useful type of measurement, since there is no amount of shielding that we can say will stop all of the radiation. The measure that is used is that amount of shielding that it takes to stop half of the amount of radiation of a given intensity. This is the so-called *half-value layer.*

Examine figure 11. At the left-hand side we show two sources of radiation, one giving off 25,600 mr/hr—the other giving off 204,800 mr/hr. The larger source has 8 times the strength of the smaller source. As we add successive half-value layers of shielding, the strength of the radiation emerging from the other side of the shielding is cut in half. It takes 7 half-value layers of shielding to reach 200 mr/hr in the case of the source emitting 25,600 mr/hr. It takes ten half-value layers to reduce the larger source to the same 200 mr/hr. Although the larger source has 8 times the strength of the smaller source, it takes only approximately 1½ times as much lead to reduce the radiation level emerging from the outside of the shielding to 200 mr/hr.

This demonstrates that the thickness of radiation shielding does not have to increase in direct proportion to the amount of radiation being shielded. A container, for instance, for a 1,000-curie radiation source does not have to be a 1,000 times as heavy as one for a 1-curie source. As a matter of fact, the container for a 1,000-curie radiation source is about 13 times as heavy as a container for a 1-curie radiation source.

This also helps us to understand that a statement such as "radiation can penetrate 22 inches of lead" of itself means nothing, because radiation can penetrate an indefinite quantity of material. The important question is, "What amount of radiation escapes from the far side of the shielding?"—the point at which the radiation can become effective on human beings.

The technician in the radiation protection field has at his disposal tables of half-value layers for various materials for various intensities of radiation, and these are used in

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Relative Efficiency Of Various Shielding Materials

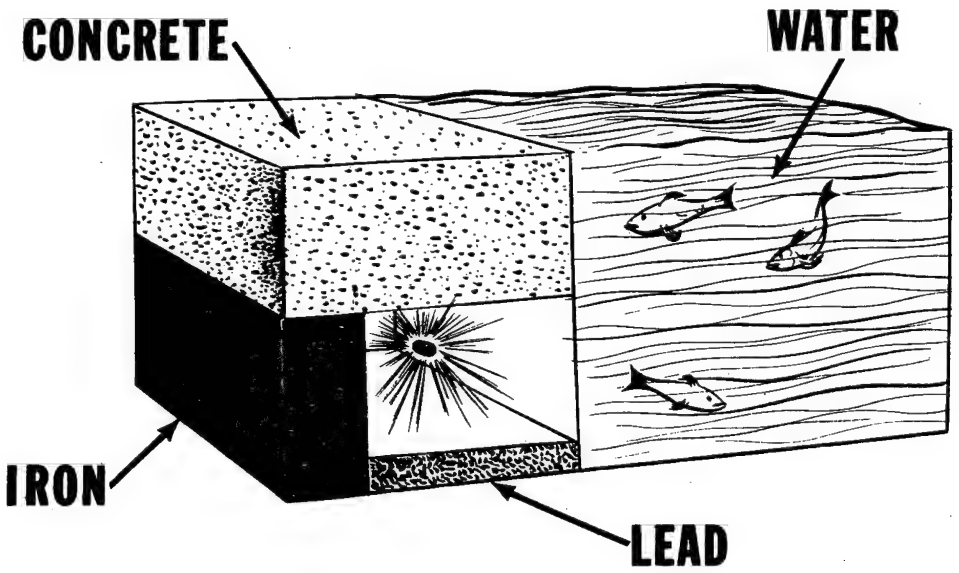


FIGURE 12

the construction of radiation shielding. After the shielding is placed, tests are made to be sure that everything is shielded to the extent shown in the calculation.

Curies

The amount of a radioactive material which is present is expressed in *curies*, or *millicuries*, or *microcuries*. A millicurie is a thousandth of a curie and a microcurie is a millionth of a curie. A curie is that amount of radioactive material which is disintegrating at the rate of 37 billion atoms per second. The curie bears no relationship to the weight of the material involved. If a material is very slightly radioactive, several thousand pounds might be required to give one curie of radioactivity. If a material is very highly radioactive, a fraction of an ounce of the material might be a curie. See Appendix B.

For instance, one curie of cobalt 60 would weigh approximately 880 micrograms, while one curie of thorium 232 would weigh 10 tons.

The curie is not a measure of the radiation hazard from the material because the curie simply tells us that so many disintegrations are taking place every second. The problem is, "What happens when an atom of this particular material disintegrates?" The hazard depends upon the quantity and type of radiation emitted.

When an atom of radioactive cobalt 60 disintegrates, two penetrating external rays are given off from each disintegration. When an atom of radioactive iron disintegrates, only one ray is given off.

When we are measuring roentgens, we are measuring these rays, and, therefore, from a curie of cobalt disintegrating, we will get twice as many rays as we will get from a curie of iron. Therefore, we will measure approximately twice as many roentgens.

As we will see later, a curie of some materials might not give us any roentgens at all, because these particular materials do not give

off penetrating external radiation when they disintegrate. So, we have no measure of the problem of dealing with the material until we are told not only how many curies or millicuries are involved but what the specific material is, just as we would have no measure of the hazard if somebody said, "I have in my basement a gallon of a flammable hydrocarbon," as this might be gasoline or it might be heavy fuel oil.

Cobalt is one of the most widely used radioisotopes; for this reason, we will work some problems in terms of cobalt.

A curie of cobalt gives off 1.6 roentgens per hour (1600 mr/hr) at a 3-foot distance. At a 9-foot distance, we have tripled the distance, so the radiation exposure is one ⅑th as much, or about 176 milliroentgens per hour. At a 15-foot distance, the distance is multiplied by 5, so our radiation level is $\frac{1}{25}$th of what it was at the 3-foot distance. Therefore, we are down to 63 milliroentgens per hour. Observe the following problems:

A man remains 6 feet from a 10 curie cobalt source for 2 hours. What is his approximate radiation exposure?

10 curie cobalt 60 source=16 r per hour at 3 feet
4 r per hour at 6 feet (¼)
4 r per hour x 2 hours
=8 rem

Man receives 8 rem exposure.

A man remains one-half hour at a distance of 9 feet from a 500 millicurie cobalt source, what is his approximate radiation exposure?

500 mc cobalt 60=½ curie
1 curie cobalt 60=1.6 r per hour at 3 feet
½ curie cobalt 60=.8 r per hour at 3 feet
½ curie cobalt 60=.09 r per hour at 9 feet (⅑)
½ hour exposure=.045 rem or 45 milirems

A man remain 1½ feet from a 10 curie cobalt 60 source for 2 hours. What is his approximate radiation exposure?

10 curie cobalt 60 source=16 r per hour at 3 feet
64 r per hour at 1½ feet
64 r per hour x 2 hours
=128 rem

Man receives 128 rem exposure.

Because of an accident, a 500-curie cobalt 60 source has been completely unshielded on a highway. This highway is a dual lane turnpike type of highway, with an approximately 90-foot strip in the middle between the two roadways. What will be the highest radiation reading on the opposite roadway?

500-curie cobalt 60 source= 800 r per hour at 3 feet
90 feet is 30 times 3 feet
Radiation level is $\frac{1}{30^2}$
$\frac{1}{900}$ of 800 r per hour
=.9 r per hour

Short Range External Radiation

We have been talking, thus far, about long-range penetrating external radiation. There is another type of radiation hazard which is less penetrating and has a shorter range. This type of radiation represent an external hazard only when we come in extremely close contact with the radioactive materials, as by handling or allowing the material to be deposited on our bodies and not promptly washing it off.

As we note in figure 13, we cannot tell which one of the 45 caliber automatics is loaded, and therefore, dangerous, and which is not, for both look alike. The same condition prevails with radioactive materials. Some radioactive materials are quite safe to handle with the bare hands; others are not—and it is impossible to tell by looking at the material whether it is safe to handle it with the bare hands. The general rule is very simple: Don't handle radioactive materials with your hands unless you know that it is safe to do so.

How Things Don't Get Radioactive

There is a widely believed misconception that radiation from radioactive materials can make other things radioactive. Some people believe that a person who works with radioactive materials will become radioactive. If a radiation source is left on a desk or table, and the source is removed, they believe that

FIGURE 13

a radioactive area is left on the surface of the table. If a radiation source is involved in a fire, and smoke and water pass through the radiation field, it is widely believed that the smoke and water will thereby become radioactive. Figure 14 illustrates this question. (We are not here considering the picking up of some of the radioactive material by the smoke or water.)

Think back a moment to the structure of the atom and the effect of the radiation from radioactive material. The radiation strikes the electron, knocking the electrons out of orbit. To make something radioactive, we must penetrate the nucleus of the atom because radioactivity originates in the nucleus. The rays from radioactive materials do not significantly penetrate the nucleus, and, therefore, cannot make something radioactive.

We will learn later on how materials do get radioactive, but let us be sure that we understand that materials do not get radioactive by being exposed to other radioactive materials. The material has been "irradiated," and if sufficient radiation has been applied to knock out a substantial number of electrons, there may be an observable *chemical* effect in the material which has been irradiated, but the material has *not* been made *radioactive.*

Nomenclature

Up to this point, we have been talking about penetrating external radiation, less-penetrating external radiation, and nonpenetrating radiation. It is time now that we provide names.

The most penetrating type of radiation is called *gamma* radiation. This radiation is

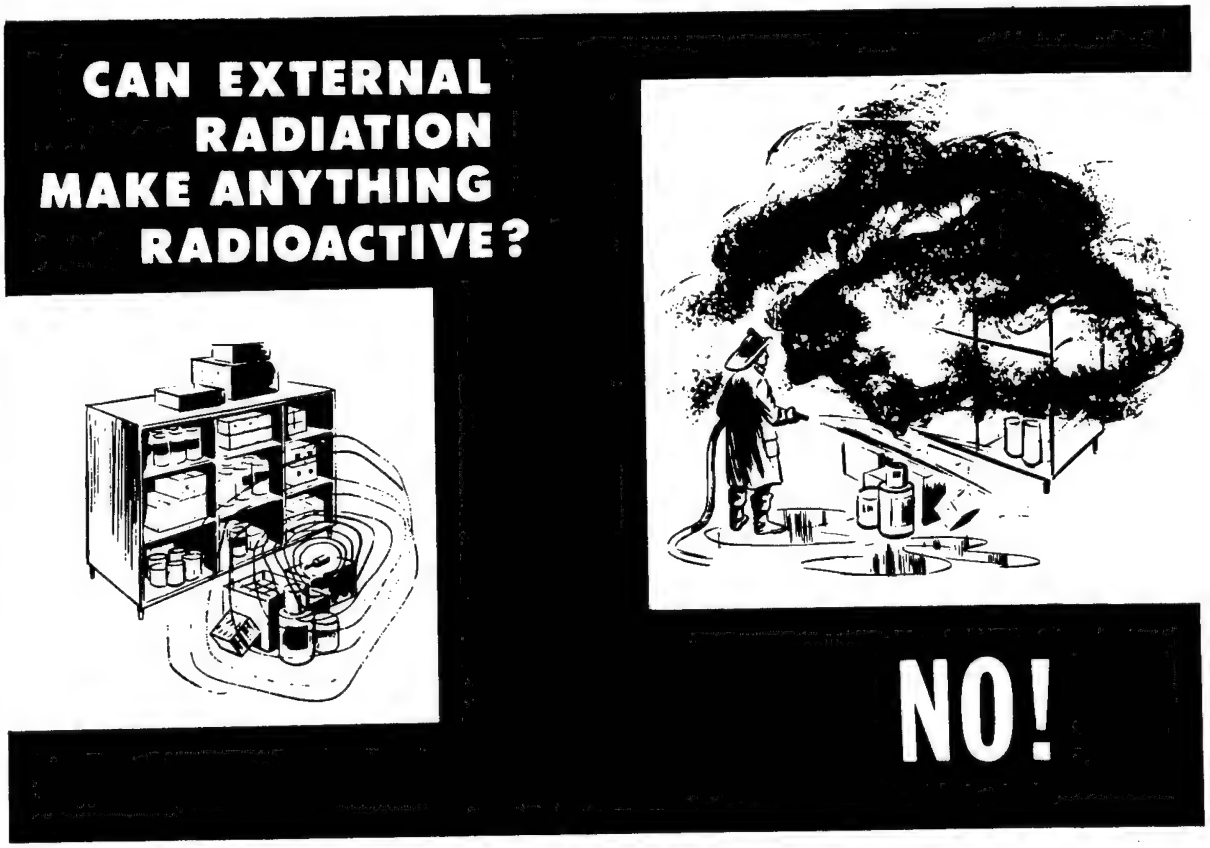


FIGURE 14

similar to X-rays, and it comes in the form of electromagnetic waves which have only energy and no substance at all.

The less-penetrating type of external radiation is called *beta* radiation. This is really a high-speed electron ejected from the nucleus. Sometimes we read of beta rays or beta particles. We are speaking about the same thing. Beta radiation has a relatively short range in the air, in general not more than a few feet.

Alpha radiation is the nonpenetrating external radiation. The alpha particle is a piece of the nucleus of the atom. It cannot penetrate the dead outer layer of the skin, and, therefore, the alpha radiation represents no external hazard at all.

In general, a radioactive material will emit either alpha radiation or beta and gamma radiation from the disintegration of any atom. For reasons which we will show later, all three types of radiation may be coming from a particular material.

External Versus Internal Hazard

We will now classify the radiations as to relative internal and external hazard.

Alpha radiation represents practically no external hazard since it cannot penetrate the dead outer layer of the skin. However, when a material which emits alpha radiation gets inside the body, the energy from these pieces of the nucleus is all taken up very close to the location where the radioactive material is deposited in the body, and there is no dead layer of skin to protect the living tissue of the

body. Therefore, alpha radiation emitters represent the worst internal hazard.

We have seen that beta radiation is relatively short-range, and the external hazard is a problem only when we are quite close to it. Therefore, if we get a material emitting beta radiation fixed in the body, it can do damage inside the body within a relatively localized area around the site of the material in the body, as does alpha radiation.

Gamma radiation, of course, represents the most severe external hazard because of the long-range and high penetration of the gamma rays. When a gamma emitter is deposited inside the body, its energy will be diffused through a larger area of the body, and also some of the rays will pass right out of the body without ever touching any of the electrons in the body.

Very often the question is asked, "Which type of radiation is the most hazardous?" This is rather like asking, "Which is more hazardous—a fall or a burn?" Probably the simplest answer is whichever does the most damage in a given set of circumstances.

Roentgen, Rad, Rem, RBE

In order to provide a means for comparing the radiation effect of different types of radiation, a number of terms have been developed and standardized. These terms include roentgen, rad, rem, and RBE.

The *roentgen* measures only X or gamma radiation in the air.

The *rad* measures the absorbed dose of any type of radiation. A rad of one type of radiation may have more effect on the body than a rad of another type.

This is expressed by the RBE (relative biological effectiveness). For instance, the RBE of gamma radiation is 1. The RBE of some alpha radiation is 20. This means that 1 rad of alpha radiation can have approximately 20 times the effect in the body as 1 rad of gamma radiation.

The *rem* is the unit of radiation dose which makes it possible to express radiation exposures of all types in one term.

Type of radiation	*Dose in rads*	*RBE*	*Dose in rems*
Gamma	1	× 1	= 1
Beta (1.0 MeV.)	1	× 1	= 1
Alpha (1 MeV.)	1	× 20	= 20

The external radiation hazard is really one of the easiest industrial hazards to control because we have instruments which can measure the hazard at the time the hazard exists. We have devices, such as film badges, and dosimeters, which will measure the exposure to personnel. If an exposure occurs without instrumentation or measuring devices being present at the time of the exposure, we can reconstruct the approximate exposure based upon time and distance from the source. The effects of serious external radiation exposures show up relatively rapidly so that we generally know soon after the incident whether there is any problem of injury to the individual or not.

Having completed our discussion of external radiation hazards, we will now proceed to the problem of internal radiation hazards.

Chapter VI

INTERNAL RADIATION PROBLEMS

By contrast with the *external* radiation exposure problem, the *internal* radiation exposure problem is a much more complicated one. Many factors are involved. There are four possible ways to get radioactive materials into the body:

1. By breathing.
2. By swallowing.
3. Through breaks in the skin.
4. By absorption through the skin.

When a radioactive material gets into the body, the first question is "How long does it stay in the body"? A high percentage of anything we inhale is immediately exhaled. Materials which we swallow which are not soluble in the body's digestive system are discharged rapidly through the feces. If a material is soluble and is breathed into the body, it will go to the blood stream. The blood stream then carries it around the body to the various organs, in effect offering the material to the organs.

The body is a chemical machine, and, therefore, the organ looks at the substance chemically. If the organ rejects the substance chemically, the blood stream takes it along trying to give it away. If no organ will accept the material, the blood takes it to the kidneys, and the kidneys dispose of the material through the urinary system. If, on the other hand, the organ has a use for the material, or if the organ thinks the substance looks like a material it can use, it accepts the substance. For instance, the bones need calcium; radium chemically looks like calcium. Therefore, when the blood takes radium to those areas where the bone is building new bone tissue, the bone accepts the radium. Thus, the radioactive material is deposited in the bone.

Some chemical substances, such as sodium and potassium, are widely used throughout the body, and, therefore, if a radioactive form of one of these elements is introduced into the body, it will be dispersed throughout the entire body. Other elements tend to concentrate in specific organs, as iodine does in the thyroid gland. The point to remember is that body organs react to a substance on the basis of its chemical nature only, without regard to whether or not the material is radioactive.

Some organs are much less "critical" to the body than others. For instance, we could not possibly live if our kidneys were removed, whereas the removal of the spleen is not nearly so critical because other organs of the lymphatic system will pick up the work load of the spleen.

The radioactive *half-life* of the material is important. We will discuss half-life more fully later. Briefly, the half-life is that amount of time that it takes half of the material to lose its radioactivity. If a material has a radioactive half-life measured in fractions of a minute, for instance, it will be dissipated very rapidly. On the other hand, if the material has an extremely long half-life, possibly measured in the thousands of years, then the rate at which it is decaying is very slow. We are only interested in that radiation effect that takes place while we are still alive. Radiation being given off in our skeletons after we die is of no interest to us. For this reason, in general, materials with radioactive half-lives from 5 to 40 years are the most significant from the point of view of half-life.

The *biological half-life* of a material is that period of time which it takes for half of the material to be excreted from the body. Some

materials are excreted quite rapidly from the body, and, therefore, will not be in it long enough to do much harm. When we combine the radiological half-life with the biological half-life, we have the *effective half-life* of the material in the body.

There is a sizable amount of medical information available on the effect of radioactive materials in the body, although, of course, much research remains to be done. Many of us are familiar with the classic cases in the field of radiation poisoning. These are the cases of the women in the radium dial painting plant in New Jersey, who pointed up the camel's hair brushes with their lips, and thus introduced radium into their bodies over a long period of time.

As a result of much work in this area, standards have been arrived at for the permissible body burden of various radioactive isotopes in the body similar to the permissible levels of radiation exposure from external radiation hazards. Working backward from the permissible body levels, permissible air concentrations of the materials were arrived at, because it is primarily by means of breathing and swallowing that the radioactive materials can get into the body on a continuous basis. These levels are stated in terms of microcuries per milliliter of air.

The hazard of absorption through the skin, where it exists, is handled by the provision of suitable protective clothing or gloves. The introduction of radioactive material through wounds is avoided by standard safety techniques to prevent injury.

Chapter VII

PROTECTION FROM INTERNAL RADIATION HAZARDS

In the handling of radioactive materials, it is possible that certain processes will permit the material to become airborne where it can be breathed by personnel. It is necessary under such circumstances that varying degrees of control precautions be taken. The simplest situation might require merely the application of ordinary hygienic procedures. The worst situation might require that the entire processing equipment be totally enclosed in order to prevent any material from escaping into the working atmosphere.

To determine whether or not the airborne concentration of the radioactive material is below the permissible standard, it is necessary to take a sample of the air which is breathed by the employees. Air samplers are nothing more than air pumps which pull a measured quantity of air through a filter paper which strains out all of the material in the air. The filter paper is then sent to the laboratory for analysis, and determination is made as to whether the air concentration is below the permissible level.

If the air concentration is found to be above the permissible level, an investigation must be made to find out why the concentration is above the permissible level. Has the procedure been changed since it was first set up? Is the ventilating system functioning properly? Are the containers being handled in the proper manner? These are some of the questions which might be gone into to find the reason for the excessive concentration.

We must, of course, bear in mind the fact that, with some exceptions, the hazard of getting radioactive materials into the body is a chronic hazard, that is to say, that in many cases it would be impossible in a single incident, or in a short space of time, to breathe in sufficient amounts of the material to constitute an appreciable portion of the permissible body burden.

In most cases, the problem is one of maintaining good techniques over an extended period of time and insuring careful compliance by all employees with all regulations, even though the violation of a regulation in a single instance might not, of itself, be extremely serious. For instance, smoking is often forbidden in the areas where radioactive materials are handled because of the obvious ease of transferring material from hand to cigarette to mouth and, thus, into the body. Eating is generally prohibited in the area for the same reason. In some cases, special work clothes are provided which are washed and remain at the plant. Sometimes it is necessary that the employees take a full shower and change clothes before they leave for home or even go to the lunchroom. In each case, the degree of precaution is based upon the nature of the hazard of the specific material being handled. No parallel can be drawn between the precautions taken in one plant and the precautions taken in another, unless we know fully the nature of the material handled and the airborne concentrations of the materials present in each of these plants.

In general, therefore, the approach to the safe handling of radioactive materials which may present an airborne radiation hazard is to confine and contain the materials at all times so as to prevent their becoming airborne. All techniques are devoted to this end. Materials are handled in closed systems, vacuum cleaners connected to a permanent system are used to pick up dust rather than brooms, ventilating systems are carefully engineered to provide air flows in the proper direction and amount,

FIGURE 15

etc. Where personnel may be exposed to airborne concentrations unavoidably, then respiratory protection can be used. This may range anywhere from the relatively simple filter type of respirator, up through filter type gas masks, to self-contained gas mask equipment, and on to a completely enclosed plastic suit with an independent air supply from the outside of the building.

Figures 15 and 16 are taken from the "Radiation Safety Primer," a publication prepared by this office and available from the Superin-

tendent of Documents at 25¢. A set of color slides and Instruction Handbook are also available. Write this office for details.

If personnel have been exposed to possibly excessive concentrations of airborne radioactive materials, it is then necessary to attempt to

KEEP YOUR HANDS OUT OF "HOT" MATERIAL.

BROOMS STIR UP DUST

USE VACUUM CLEANERS

WASH UP BEFORE YOU EAT AND BEFORE YOU GO HOME.

DO NOT EAT IN AN AREA WHERE RADIOACTIVE MATERIALS ARE PROCESSED.

EAT *in the* LUNCH ROOM

— WHETHER YOU BRING IT OR BUY IT.

FIGURE 16

determine how much of the radioactive material the man has gotten into his body. These so-called bio-assay techniques are, in some bases, costly, time consuming, and not very accurate. They may include the analysis of breath samples, stool samples, urine samples, blood samples, bone marrow samples, etc.

What can be done for a man who has received an excessive concentration of a radioactive material in the body of a type which will not correct itself by the natural processes of elimination but tends to remain in some critical organ of the body? Various methods are being studied to accelerate the removal of the material from the body. At this writing, these are of limited value.

If your work brings you into contact with airborne radioactive materials, it is necessary that you comply strictly with all of the safety precautions which are laid down. Under no circumstances should procedures be violated or short cuts be taken on the basis that one or two exposures won't hurt anybody. While this may literally be true, the effect of such a disregard of such regulations over the long run may prove extremely injurious.

In an emergency situation, particularly when the ventilating system or containment system has been disrupted, there is no readily available procedure for making an immediate analysis of the airborne radiation hazard. The only overall answer is that all personnel who must enter the area should wear masks with a self-contained air supply to protect them against breathing or swallowing any radioactive material. In such a mask, the wearer is completely cut off from the atmosphere surrounding him. In a filter type of mask, the man breathes the surrounding air through a filter. Certain filter masks are quite satisfactory for use in certain situations. Upon leaving the emergency area, such personnel should immediately shower and change clothing to remove any remaining radioactive material. These precautions will provide real assurance that the personnel have received no deposition of radioactive materials in their bodies.

Chapter VIII

CONTAMINATION

Where radioactive materials which can be easily spread around are handled, all personnel must be alert to the possibility of the spread of radioactive *contamination.* Like all other radiation problems, the situation may be relatively minor or extremely severe, depending upon the nature of the material, the type of radiation given off, and requirements for use of the area. For instance, in a laboratory doing very precise radiation measurements, a very small amount of radioactivity insufficient to represent any danger to health may interfere seriously with the work being performed because the background level in the laboratory is increased by the contamination. At the other end of the scale, it is possible to contaminate a building so severely that it is cheaper to abandon the building than to attempt to decontaminate it.

The hazards from radioactive contamination may be from *alpha*, *beta*, or *gamma* radiation. If an alpha emitter is deposited on a surface, such as a wall or floor, this, in itself, would represent no problem, since the short range of the alpha radiation does not permit it to reach anybody and do him any harm. However, alpha-emitting contaminants on a surface must be dealt with because there is always the possibility that they will become airborne and thereby breathed by the people in the area.

Beta emitters present both the possibility of becoming airborne and creating high radiation levels near the surface of the contaminated area.

If the contaminant is a gamma emitter, then a high radiation area may be set up in the entire contaminated area due to the gamma rays coming off of the tiny bits of radioactive materials which are spread all around the area. *Of course, materials emitting all three types of radiation may be present.*

Prevention of the spread of contamination takes many forms. Procedures for the control of materials, covering of containers, enclosure of processes, etc., should be complied with carefully. Clothing which is restricted to one area should not be worn when passing from a contaminated area to a clean area. In many plants, this is enforced by marking clothing to be worn only in a contaminated area by such devices as a red collar, or by other means. Personnel working with radioactive materials who might get hands or feet contaminated should not leave the contaminated area for a clean area without first checking at a hand and foot counter, or other monitoring device. A hand and foot counter is a device which automatically registers the radioactive contamination on the hands and feet. If the readings are above the permissible background level, the person should not leave the area without cleaning up.

In areas where contamination may reasonably be expected to occur, oftentimes special preparations are made to make it easy to decontaminate. Paper tissues are spread on table tops and on laboratory benches to gather up the contamination. Special strippable films are used on wall surfaces so that the paint can be easily stripped off and replaced when it becomes contaminated. The design of air conditioning systems should be carefully thought out to avoid the spread of contamination through the air conditioning system from one area to another. Contaminated equipment being removed from the plant must also be given special handling. In some cases, this material is encased in plastic prior to being

removed. A special cap is placed on the end of contaminated pipe or the material may be thoroughly decontaminated before removing it from the area.

Clean up

When an area has been contaminated and it is necessary to clean up the situation, there are a number of possible techniques, depending upon the nature of the problem.

If the contaminant has a short *half-life*, it is sometimes simpler to allow the area to remain idle until the radioactivity has died off by the natural process of the passage of sufficient half-lives. If we had a reading of 100 mr per hour in a room contaminated with a 24-hour half-life gamma emitter, in 24 hours the reading would be down to 50 mr; in another 24 hours it would be down to 25 mr per hour; in another 24 hours it would be down to 12½ mr per hour, etc. See figure 17.

A useful rule of thumb is the fact that the passage of 7 half-lives will bring a radiation level down to 1 percent of what it is at the present time, and in 10 half-lives, the level will be down to 0.1 percent.

If the material is an alpha emitter, it can be fixed to the surface by painting, since the alpha radiation cannot penetrate the paint. Floor tile can be removed and replaced in order to remove contamination. In general, however, contamination is removed by scrubbing of surface with detergents which are best suited to remove the particular material with which the surface is contaminated. It is im-

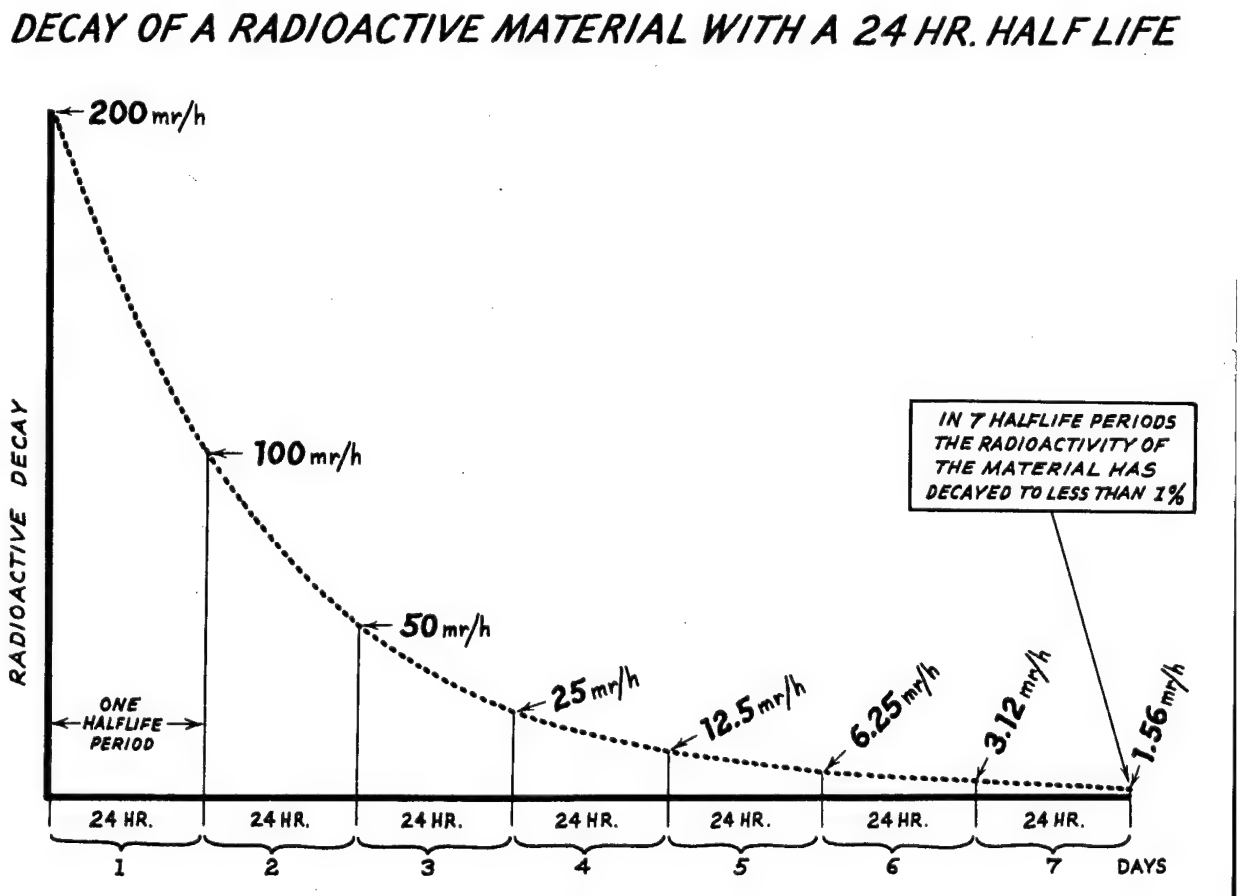


FIGURE 17

possible to "neutralize" radioactivity as we might think of neutralizing an acid spill with bicarbonate of soda. Radioactive contamination is simply radioactive material some place where we do not want it, and the only real solution to the problem is to pick up the material and remove it if it will not decay fast enough to suit our purpose.

Contamination is most easily spread during an emergency situation, such as an explosion or a fire. An ordinary rubbish fire in a building will bring about an odor of smoke in many points in the building far removed from the source of the fire. When we smell smoke, we are actually smelling tiny bits of ash which have reached our nostrils from the fire and were originally part of the paper which was ignited. Radioactive materials involved in a fire can spread very easily due to the air currents set up by the fire. They can also spread easily if, by some accident, they are introduced into the air conditioning system, or if they are spilled on the floor so they can be tracked around. Personnel working in an area contaminated during an emergency must be extremely cautious that, in their haste to deal with the emergency, they do not make the situation much worse by transferring contamination to the clean areas by means of their clothing, tools, equipment, etc.

Since it is extremely difficult at the scene of an emergency to set up adequate monitoring procedures to make sure that nothing contaminated leaves the area, *it is most important that adequate preplanning be done for possible emergencies, with radiation contamination problems considered realistically.* The same type of preplanning should be carried on whenever maintenance or repair work is to be done in a contaminated area.

Chapter IX

INSTRUMENTS AND PERSONNEL DOSIMETRY

We are all familiar with the fact that radiation can be detected by instruments designed for the purpose. To the average person, all such instruments are "*geiger counters.*" A geiger counter is but one of the available types of radiation detection instruments. It is essentially a low-level instrument since the maximum reading available on most geiger counters is 40 or 50 mr per hour. Most geiger counters will register both gamma and beta radiation. By closing a shield which covers the GM-tube, beta radiation which cannot penetrate the shield is screened out, and only the gamma radiation gets through. Beta radiation is, therefore, computed by taking the open window reading (beta and gamma), and then subtracting the closed window reading (gamma only).

Higher levels of beta and gamma radiation are read with an instrument called an *ionization chamber.* Ionization chambers for Civil Defense use are designed to read as high as 500 r per hour.

A *scintillation counter* is a very precise radiation-measuring instrument which will detect minute quantities of gamma radioactivity.

Since alpha radiation has such a very short range in air and little or no penetrating ability, it must be detected on special alpha measuring meters, and the measuring area of the meter must be brought directly to the contaminated surface. When an area has been contaminated with a pure alpha emitter, the entire surface must be scanned thoroughly, inch by inch, to detect the location of the contamination. Since the alpha radiation has a very limited range, the contamination level at one point is no indication of what the contamination level may be at another point nearby.

Alpha radiation contamination levels are generally stated in terms of so many disintegrations per minute per 100 square centimeters of surface. Where the surface is irregular, and the flat surface of the instrument cannot be brought to bear, a piece of cloth or tissue is used to wipe a measured area of the surface. Then this piece of paper is measured to get a figure of the contamination on the surface.

The same wipe technique is used for beta- or gamma-contaminated surfaces to determine how much of the contamination is removable and how much is fixed to the surface.

All of the radiation detectors are *rate meters*, that is, they measure the rate of radiation being received by the instrument at the time you read the instrument. If the instrument is removed from the radiation field, the needle will, of course, return to background and there will be no indication of the radiation levels to which the machine has been subjected.

Developments are rapidly being made in the field of radiation instrumentation, and advice on the purchase of any radiation detection instruments should be obtained from persons who are in a position to keep abreast of the latest developments. All radiation detection instruments, however, require skilled maintenance and calibration if they are to serve the purpose for which they are intended. The mere purchase of an instrument or instruments, of itself, serves little purpose. A complete program should be set up designed to insure that instruments will be in operating condition when needed and will be as accurate as necessary for the service intended.

Dosimetry

For the protection of individuals, we need devices which will measure the accumulated radiation exposure. These come in two types —*film badges*, and *pencil dosimeters.*

Film badges are a bit of dental X-ray film worn in a special holder. The X-ray film is sensitive to radiation in various ranges and when developed by standard photographic techniques, the film will be darkened in proportion to the amount of radiation received. When the darkening of the film is compared with the darkening of similar films which have been exposed to a known amount of radiation, the amount of radiation which the film badge has received is indicated. The film badge will indicate the radiation which the man has received only if it is always worn when in the radiation area and if it is not exposed to radiation when it is not being worn by the man to whom it is assigned. Film badges provide a permanent record of radiation exposure, but not an immediate one, because of the time required for developing the film and reading the badges.

For a ready available accumulative record of radiation exposure, a pencil dosimeter is used. A pencil dosimeter is a device which will record the radiation which is received, starting from zero, when the device is properly set, to the limit of the scale of the particular dosimeter. Some dosimeters can be read directly by holding them up to the light; others must be read in a reading device provided for the purpose. Dosimeters can be caused to give false high readings by being dropped or damaged by electrical leakage, and, therefore, are generally worn in pairs.

The primary rule for wearing personnel measuring devices is to wear the device provided at all times when in a radiation area and to protect it from radiation exposure when it is not being worn.

Film badges and pencil dosimeters will not record alpha radiation, of course. This is of no consequence since external alpha exposures are no hazard.

Chapter X

A LITTLE RADIATION PHYSICS

We have seen that material does not become radioactive by being subjected to alpha, beta, or gamma radiation from a radioactive material, and that a material does not become radioactive when it is contaminated with a radioactive material.

We do know that things can be made radioactive somehow or other, and we should have some idea of how this comes about.

In addition, we should have a basic understanding of the atomic fission process and how the energy available from the splitting of atoms can be used to generate electrical power. Furthermore, we should be aware of the problem of the handling of so-called *fissionable* or *critical* materials. Finally, there are some unanswered questions about the decay of radioactive materials. How can we read gamma radiation from a radium dial wrist watch when radium is a pure alpha radiation emitter?

It is necessary, therefore, that we delve a little further into the structure of the atom at this point.

Earlier we discussed the nature of matter, and we left the description of the atom at about the following point. The atom consists of a heavy, dense, hard nucleus, which contains practically all of its weight, but which is surrounded at quite some distance from the nucleus with a number of electrons which have practically no weight at all.

It is now necessary for us to examine the structure of the nucleus in a little greater detail. The nucleus consists of little individual balls of matter, all of them about the same size in all atoms. Some of these little balls of matter have a positive electrical charge. These are called protons. Others have no electrical charges at all; they are electrically neutral. These are called neutrons.

For each positively charged *proton* in the nucleus, there is a negatively charged electron in the orbit. The number of protons in the nucleus, therefore, determines the number of electrons in the orbit. The number of protons also determines the nature of the element. In nature, we find elements with the number of protons ranging all the way from one proton (hydrogen) to 92 protons (uranium). Each time we change the number of protons, we have an entirely different element.

The number of *neutrons* in the nucleus may range from none to almost 150. In the case of certain elements, we find that different atoms of the same element have the same number of protons but have different numbers of neutrons. To the chemist, these are the same element because the chemist really works with the electrons, and since all of these atoms have the same number of protons, they will have the same number of electrons.

Since they have a different number of neutrons in the nucleus, however, the various atoms of the same element will not all weigh the same.

To the nuclear physicist, these are different substances of the same chemical form but varying in their atomic weight. These are called *isotopes*. Some of the isotopes may be unstable, and, therefore, radioactive. Some of the isotopes may be stable and not radioactive.

The atomic *number* of a substance is the number of protons in the nucleus. The atomic *weight* of a substance is the sum of the number of protons and neutrons. Thus, two isotopes of the same substance will have the *same* atomic number but will have *different* atomic weights.

Figure 18 shows various isotopes of hydrogen as found in nature. Note that the heavier iso-

ISOTOPES

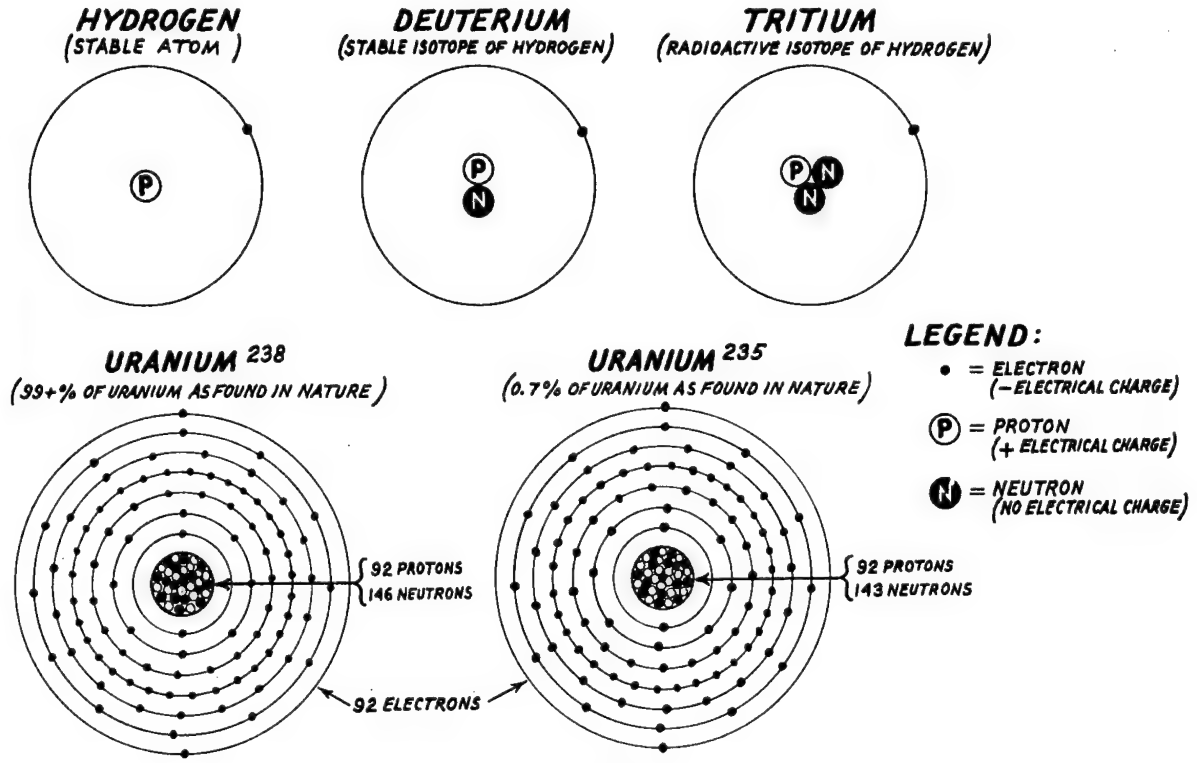


FIGURE 18

topes are a very small fraction of 1 percent of the total amount of hydrogen we find in nature. We know that water consists of molecules made up of two parts of hydrogen and one part of oxygen. If we make some water in which the hydrogen is not the normal isotope of hydrogen with one proton but the deuterium isotope with one proton and one neutron, we will make a water that looks like water, tastes like water, and, from the chemical point of view, is water. However, from a neuclear point of view, this is so-called heavy water because it is made with the heavier isotope of hydrogen.

Figure 18 also shows us two different isotopes of uranium. One is called uranium 238; the other uranium 235. Both of these will react chemically in exactly the same way. Therefore, to the chemist, a mass of material consisting of these two isotopes is uranium.

Atomic Disintegration

Let us consider now what happens when a radioactive isotope gives off radiation, and let us follow one atom of uranium through its successive disintegrations. We start with an atom of uranium 238, which has 92 protons and 146 neutrons, as shown in figure 19. Follow the process step by step on the chart.

Uranium 238 emits an alpha particle. An alpha particle consists of two protons and two neutrons, and, therefore, it is obvious that it is an atom in its own right. It is the nucleus of the helium atom, helium being that atom which has two protons and two neutrons. With

DECAY OF A URANIUM ATOM

ELEMENT AND ATOMIC WEIGHT	TYPE OF RADIATION EMITTED	NUMBER OF	
		PROTONS	NEUTRONS
URANIUM-238	ALPHA PARTICLE	92 -2	146 -2
THORIUM-234	BETA PARTICLE	90 +1	144 -1
PROTACTINIUM-234	BETA PARTICLE	91 +1	143 -1
URANIUM-234	ALPHA PARTICLE	92 -2	142 -2
THORIUM-230	ALPHA PARTICLE	90 -2	140 -2
RADIUM-226	ALPHA PARTICLE	88 -2	138 -2
RADON-222	ALPHA PARTICLE	86 -2	136 -2
POLONIUM-218	ALPHA PARTICLE	84 -2	134 -2
LEAD-214	BETA PARTICLE	82 +1	132 -1
BISMUTH-214	BETA PARTICLE	83 +1	131 -1
POLONIUM-214	ALPHA PARTICLE	84 -2	130 -2
LEAD-210	BETA PARTICLE	82 +1	128 -1
BISMUTH-210	BETA PARTICLE	83 +1	127 -1
POLONIUM-210	ALPHA PARTICLE	84 -2	126 -2
LEAD-206	STABLE ATOM	82	124

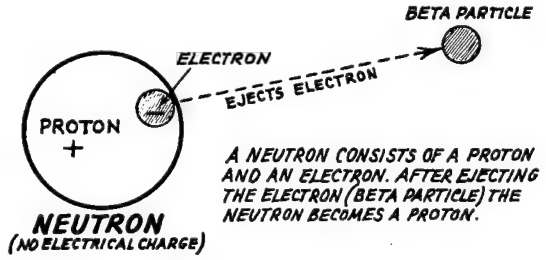


FIGURE 19

the alpha particle thrown out, we now have 90 protons and 144 neutrons. Our nucleus now weighs 234 units, and since the number of protons has been changed, it is no longer *Uranium*, but is, in fact, *Thorium*.

Thorium 234 does not emit an alpha particle but does emit a beta particle. Where does the beta particle come from? Remember that we said a neutron was electrically neutral. We know that an electrically neutral state can be reached when positive and negative charges balance one another. Let us consider that a neutron consists of a proton with an electron tightly tied onto it as shown in figure 19. The negative charge of the electron balances the positive charge of the proton, so we have a neutron. When this negatively charged electron is emitted as a beta particle, the remainder is no longer electrically neutral, but now has a positive charge, so we have changed a neutron to a proton. We have, in effect, added one proton and subtracted one neutron. We now have 91 protons and 143 neutrons. The weight is still 234, but since we have changed the number of protons, we have changed the nature of the element, and it is now an atom of *protactinium*.

Protactinium also emits a beta particle so we add 1 proton, and subtract 1 neutron, leaving 92 protons and 142 neutrons. Its weight is 234, but our element is, of course, again *uranium*.

Uranium 234 emits an alpha particle, so we subtract 2 neutrons and 2 protons, and we now have 230 particles in the nucleus. Since the number of protons is back to 90, we have *thorium 230*.

Thorium 230 emits an alpha particle. Subtract 2 protons and 2 neutrons. We now have a weight of 226, and since we have only 88 protons in the nucleus, we now have the element *radium*.

Radium emits an alpha particle, so we lose 2 neutrons and 2 protons, and have 86 protons and 136 neutrons. Our element is now *radon 222*, which is a gas.

Radon 222 emits an alpha particle, leaving us with 84 protons and 134 neutrons. Again we have a different element—*polonium 218*.

Polonium emits an alpha particle, which leaves us with 82 protons and 132 neutrons, *lead 214*.

Lead 214 emits a beta particle which increases our number of protons by 1 and decreases our number of neutrons by 1, leaving us with 83 protons and 131 neutrons. This gives us *bismuth 214*.

Bismuth 214 emits a beta particle which adds 1 proton and subtracts 1 neutron, leaving us

84 protons and 130 neutrons. This is polonium 214.

Polonium 214 emits an alpha particle which costs us 2 neutrons and 2 protons, bringing us down to 82 protons and 128 neutrons for a mass of 210, and the element is *lead 210.*

Lead 210 emits a beta particle, giving us 83 protons and 127 neutrons, which is *bismuth 210.*

Bismuth 210 emits a beta particle. Add a proton and subtract a neutron, and we have 84 protons and 126 neutrons—*polonium 210.*

Polonium 210 emits an alpha, which leaves us with 82 protons and 124 neutrons. The total weight is 206; the element is *lead 206.*

Lead 206 is stable and not radioactive, and we have reached the end of the line.

Well, that's fine, and all very interesting, and accounts for beta and alpha radiation, but what about gamma radiation? Where does that come from? Gamma radiation originates when the discharge of one of these particles from a nucleus does not take sufficient energy with it to leave the nucleus in quite a contented state. If the particle leaving the nucleus does not take with it all of the energy that the atom would like to get rid of in this particular disintegration, it throws off some of the energy in the form of gamma radiation.

The foregoing makes it clearer to us why we can detect gamma radiation from a radium dial wrist watch. Radium is a pure alpha emitter, but as the decay process goes on through the decay chain, the "daughter products" of the radium start to build up, and it is from the decay of the various "daughter products" that we receive the gamma radiation. Pure elemental radium, freshly prepared, represents only an alpha hazard and could safely be handled with the bare hands as far as external hazard is concerned. (Of course, handling it with the bare hands is not a good idea because of the possibility of introducing some radium into the body by this means.) After the passage of some time, however, the "daughter products" start to build up, and alpha, beta, and gamma radiation are all being given off from the radium and its associated daughters.

It is impossible for us to look at any one atom and predict exactly when this disintegration process will take place, but if we have a large number of the atoms, we can determine that half of the atoms will disintegrate in a given period of time. This is the so-called half-life of a radioactive material and may range from fractions of a second up to thousands of years. The shorter the half-life, the more highly radioactive the material will be.

Isotopes with very short half-lives are not very useful because they will decay so rapidly that they cannot be put to effective use. Isotopes with half-lives measured in hours or days, can be put to practical use, but this requires close scheduling of the use of the isotopes with its manufacture, air express shipment, immediate pickup, etc.

Radiation Energy

From the natural decay of radioactive materials, therefore, we get energy which can be used in a number of ways. The energy emits signals which can be detected, and thus we can trace processes in man, plants, and animals. It will make the air electrically conductive, and we can use it to bleed off static electricity. It has the power to destroy living tissue, and, therefore, we can use it to kill off bacteria or malignant growths in man. It has the power to bring about changes at certain stages in chemical processes just as other applications of energy, such as heat and light can do, and, therefore, we find it useful in the manufacture of certain products. In small amounts it can be converted into electrical energy.

However, as important as this source of radiant energy is, we cannot use it for an energy source such as we need for the generation of substantial quantities of electrical power to replace or to supplement our rapidly exhausting stock of fossil fuels, such as oil,

coal, and natural gas, or our limited supplies of water power. In order to do this we have to look to another physical property of a very few of the radioisotopes. This is not radiation at all, but *atomic fission.*

Fission Energy

Einstein demonstrated mathematically that mass could be converted to energy. If we were to take a large heavy atom like uranium and break it up into two smaller atoms, we would find that the neutrons and protons in the two smaller atoms do not weigh quite as much as the neutrons and protons in the uranium atom did. Some of the mass of the nucleus of the atom has been converted to energy.

A neutron makes a good atomic bullet because it is electrically neutral, and, therefore, is not repelled by the positive charge of the nucleus. So, if we fire a neutron at a uranium nucleus at the proper speed, the neutron will enter the nucleus, break it up into two smaller atoms, and a certain amount of energy will be released. The problem, of course, is that it takes quite a bit of effort to fire the neutron in the first place, and this process, by itself, would not be productive of any useful energy.

The uranium 235 isotope is unique in the fact that when it is hit by a neutron and the atom is broken up into smaller particles, some of the neutrons in the uranium nucleus in turn become nuclear bullets and fission other atoms of the same material. This chain reaction, by which one neutron can be used to release the energy from an atom, and, in turn, create more than one additional bullet which will carry on the process, is the secret of releasing massive quantities of energy from the atom.

Chapter XI

ATOMIC FISSION

We now see that there is nothing equivalent between the terms "radioactive" and "fissionable." Just because a material is radioactive, it is not necessarily fissionable, and most of the radioisotopes which are handled in commerce and industry are not fissionable. Many people are convinced, for instance, that if a person had a sufficient quantity of cobalt 60 on hand, a nuclear chain reaction could be brought about. This, of course, is not the case. We must have a material capable of keeping up and *multiplying* the chain reaction process so that a large number of fissions can be made to take place in a relatively short space of time.

There are only two materials readily available to us which have this property. One is uranium 235, which is an isotope of uranium, about $\frac{1}{140}$th of uranium as it is found in nature, the balance being mostly U^{238}. The other fissionable material is plutonium. Plutonium is not a natural element, but a man-made element created from uranium in nuclear reactors.

If we take some uranium as we find it in nature, and, by a complicated physical process,

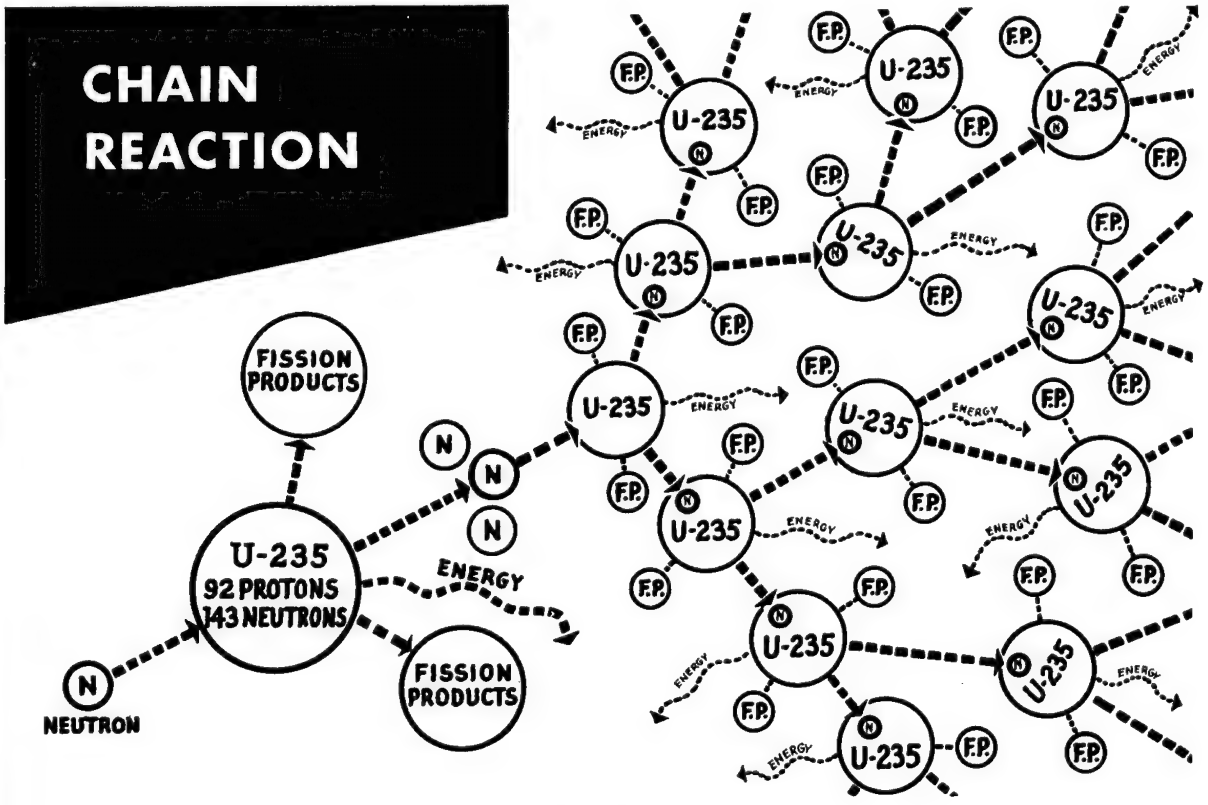


FIGURE 20

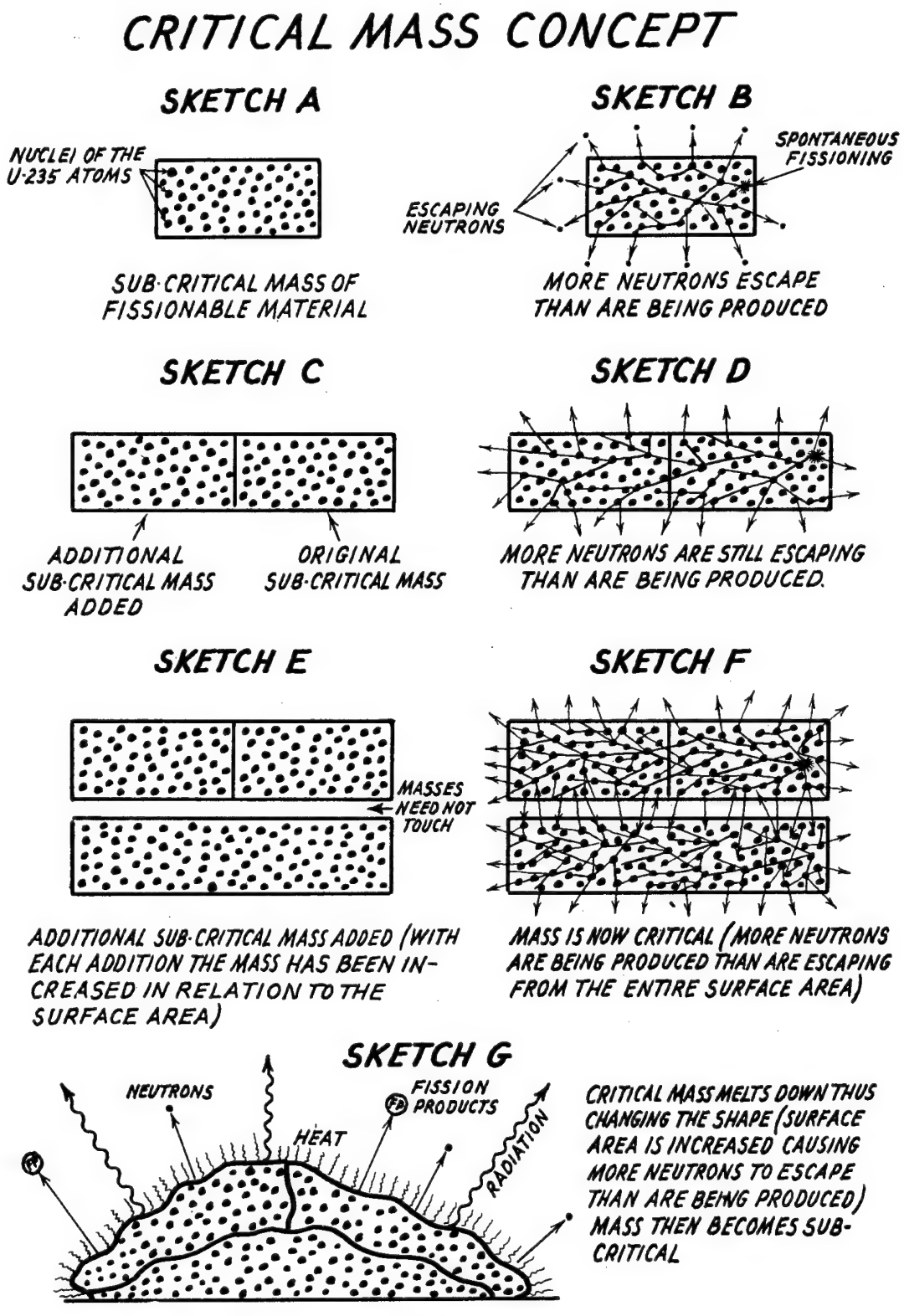

CRITICAL MASS CONCEPT
SKETCH A
NUCLEI OF THE U-235 ATOMS
SUB-CRITICAL MASS OF FISSIONABLE MATERIAL
SKETCH B
SPONTANEOUS FISSIONING
ESCAPING NEUTRONS
MORE NEUTRONS ESCAPE THAN ARE BEING PRODUCED
SKETCH C
ADDITIONAL SUB-CRITICAL MASS ADDED
ORIGINAL SUB-CRITICAL MASS
SKETCH D
MORE NEUTRONS ARE STILL ESCAPING THAN ARE BEING PRODUCED.
SKETCH E
MASSES NEED NOT TOUCH
ADDITIONAL SUB-CRITICAL MASS ADDED (WITH EACH ADDITION THE MASS HAS BEEN INCREASED IN RELATION TO THE SURFACE AREA)
SKETCH F
MASS IS NOW CRITICAL (MORE NEUTRONS ARE BEING PRODUCED THAN ARE ESCAPING FROM THE ENTIRE SURFACE AREA)
SKETCH G
NEUTRONS
FISSION PRODUCTS
HEAT
RADIATION
CRITICAL MASS MELTS DOWN THUS CHANGING THE SHAPE (SURFACE AREA IS INCREASED CAUSING MORE NEUTRONS TO ESCAPE THAN ARE BEING PRODUCED) MASS THEN BECOMES SUB-CRITICAL

FIGURE 21

take out many of the atoms of uranium 238, we will, thereby, increase the proportion of uranium 235. This is so-called enriched uranium. This is to say, it has been enriched in the proportion of the fissionable uranium 235 isotope. The degree of enrichment is expressed in percent. Normal uranium is 0.7 percent enriched. This is uranium as we find it in nature. If we take out enough of the U^{238} isotope in the gaseous diffusion plant at Oak Ridge, we increase the percentage of U^{235} in the resultant product. If we increase the percentage to 2 percent, we have 2 percent enriched material. If we increase the percentage of U^{235} to 10 percent, we have 10 percent enriched uranium, which is still uranium. Chemically, it reacts like uranium; it looks like uranium; it is uranium. The idea is quite similar to picking slate out of low-grade coal to increase the BTU content, per ton, of the resultant product.

Figure 20 shows us what happens when a neutron strikes an atom of fissionable material, whether it is enriched uranium or plutonium. The atom splits, some energy is released, smaller atoms (fission products) are left from the pieces of the uranium atom, and 1 to 3 more neutrons are freed to continue the fission process.

Since some of the atoms of uranium are spontaneously fissioning all of the time, it is quite possible for a spontaneous chain reaction to take place if a sufficient quantity of the material is assembled in the proper shape. The quantity of a fissionable material which will provide a self-sustaining chain reaction is known as the critical mass of the material.

Let us see what happens as we assemble a critical mass piece by piece. Figure 21 shows us what happens step by step.

In "sketch A" we see a piece of fissionable material. We are no longer concerned with the electrons. Each one of the dots represents a nucleus of a uranium 235 atom. In "sketch B" we see what happens when one of the atoms spontaneously fissions and throws out neutrons which start the chain reaction. Even though uranium is a heavy, dense material, it is still mostly space. Because we have a relatively small amount of the material in proportion to the surface area, neutrons can readily escape from the mass. The result is, that while little firecrackers of chain reaction are starting from time to time, so many neutrons get lost through the surface that the process does not multiply itself.

In "sketch C" we add to the first subcritical mass of fissionable material an additional subcritical mass of fissionable material. Some of the neutrons which were escaping freely from the first piece of fissionable material now find targets in the second piece of fissionable material, and additional fissions take place as shown in "sketch D." However, we still have such a large surface to mass ratio that the neutrons readily escape out of the mass, and we still cannot get a self-sustaining chain reaction because more neutrons are being lost than are being created.

"Sketch E" shows us what happens in this particular instance when we add a third piece of fissionable material. We notice that we have greatly increased the mass of the material without greatly increasing the surface area. As the chain reaction starts and the neutrons start to multiply as shown in "sketch F," there is insufficient surface area for the neutrons to escape. As soon as we make one more neutron than we have lost, the mass is critical, and the multiplication of the chain reaction starts to increase at a fantastic rate. *The fact that three pieces are used here is only for example and is not related to any specific situation.*

Because of the energy being released, the mass starts to heat up. As the fissionable material heats, it eventually reaches the melting point. When a mass melts down, the surface area is increased, the neutrons can again freely escape in a greater number than they are being generated, and the result is that the chain reaction comes to a halt as shown in "sketch G." This will all take place in an instant.

At the time the process was going on, there was a burst of gamma radiation, which is

extremely hazardous to people in the area. There was a burst of neutron radiation, which is also hazardous to those immediately present, and a certain amount of heat was given off. In addition, fission products, giving off a variety of radiation, and with a variety of half-lives, were created from the fissioned atoms of the fissionable material. Because of the heat generated, the fission products may be spread around the area by convention currents of hot air, so that the area may be highly contaminated with radioactive material.

If any person was present close by when this took place, he could be seriously injured and in danger of death. A person entering this area afterwards would necessarily have to be protected against the gamma radiation from the fission products by restricting his time in the area to the minimum, and against the beta radiation from the fission products by suitable clothing.

There would not be an atomic bomb type explosion in this accident, however, because we did not have the hardware that goes to make an atomic bomb. The situation is similar to that of a firecracker. When we light a firecracker in the normal manner, we have an explosion. When we take the firecracker, break it open, and spread the powder out on the ground, and then ignite the powder, we get the same energy release, but we do not have an explosion because we do not have the physical form necessary to make a firecracker.

So far, we have not seen anything really useful. We know that if we take a fissionable material and assemble a critical mass of it in our laboratory that we can have a serious accident; the person performing the experiment may be killed (though persons as close as 12 feet have survived such an accident); and the laboratory may be heavily contaminated.

Let us see how we might control this operation to our benefit. Figure 22 shows us the same array of pieces of fissionable material, but, in this case, we have placed between our two subcritical masses a rod made of an element called boron. Boron has a characteristic that it soaks up neutrons as a sponge soaks up water. It is called a neutron absorber. Because of this, we would not get any appreciable interaction between any neutrons being thrown off by each of the pieces of fissionable material as the boron would have absorbed the greatest percentage of the neutrons reaching it. If we slowly pulled out our boron rod until we reached the point where we were just making enough neutrons to keep our chain reaction going, our uranium would heat up.

If we removed the heat from the uranium with a heat exchange medium, such as water, an organic solvent, a gas, or a liquid metal, we would keep the uranium from getting too hot, and we could exchange the heat from the cooling medium to water to make steam. When we have done this, we have built an *atomic power reactor.*

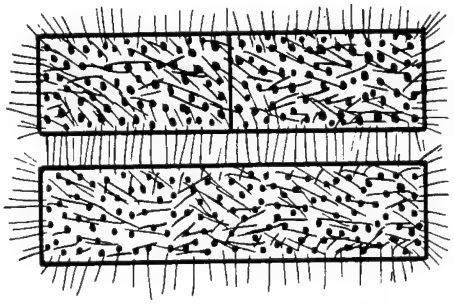
This is the basic principle of the control of atomic energy for the generation of power. Some reactors use natural uranium, rather than enriched uranium. Some work is being done on plutonium fuel reactors. Reactors vary in the arrangement of the material. In some reactors, the fuel is placed in the form of solid rods; in other types the fuel is slurried in a liquid. Reactors vary also in the nature of the material used to cool the reactors.

If something starts to go wrong with our "reactor," we would simply shove the boron rod in all the way, absorb neutrons, and our reactor would stop instantly. This emergency shutdown of a reactor is what is known as the "*scram.*" Boron and similar materials which stop the chain reaction are called reactor "*poisons.*"

Figure 23 shows us how we use a reactor to create radioactive isotopes and to change elements from one species to another. Into a hole in our reactor, we insert some cobalt metal. Cobalt, as we find it in nature, has 27 protons and 32 neutrons. There is no other natural isotope of cobalt. When we shove a rod of cobalt into the reactor, the millions and billions of atoms of cobalt are subjected to an intense bombardment of neutrons, the so-called "*neu-*

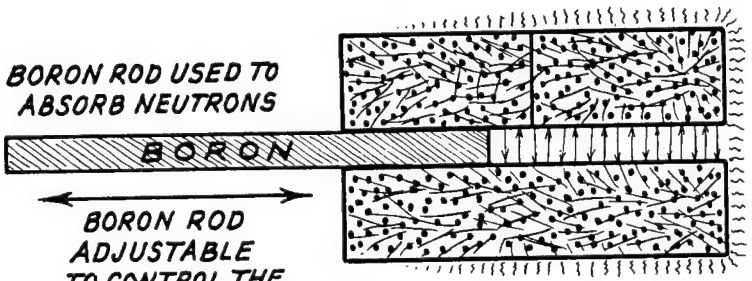
ATOMIC REACTOR CONCEPT

SKETCH A



MASSES OF FISSIONABLE MATERIAL BUILT UP TO PRODUCE A CRITICAL MASS WITH AN UNCONTROLLED CHAIN REACTION

SKETCH B



EVEN IN A CONTROLLED CHAIN REACTION THE HEAT PRODUCED WOULD CAUSE A MELTDOWN OF THE MASS, IF NOT REMOVED.

SKETCH C

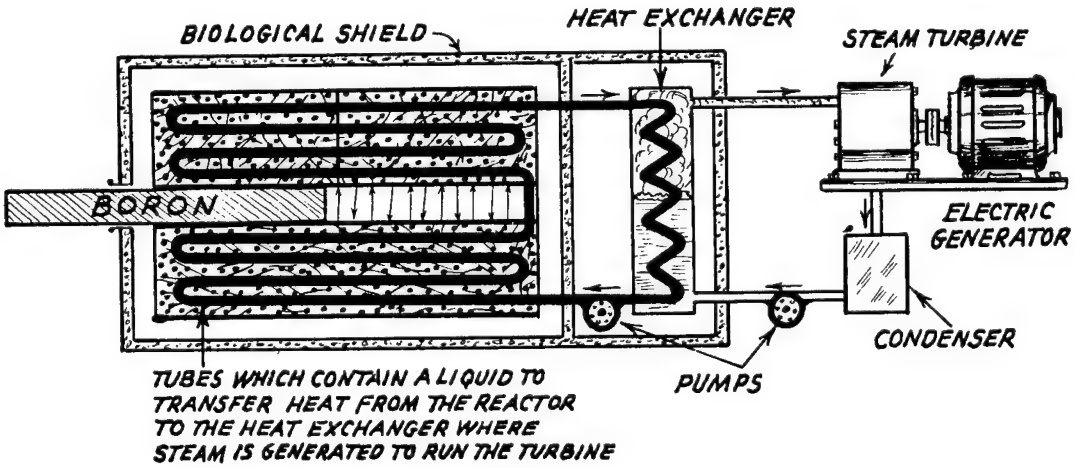


FIGURE 22

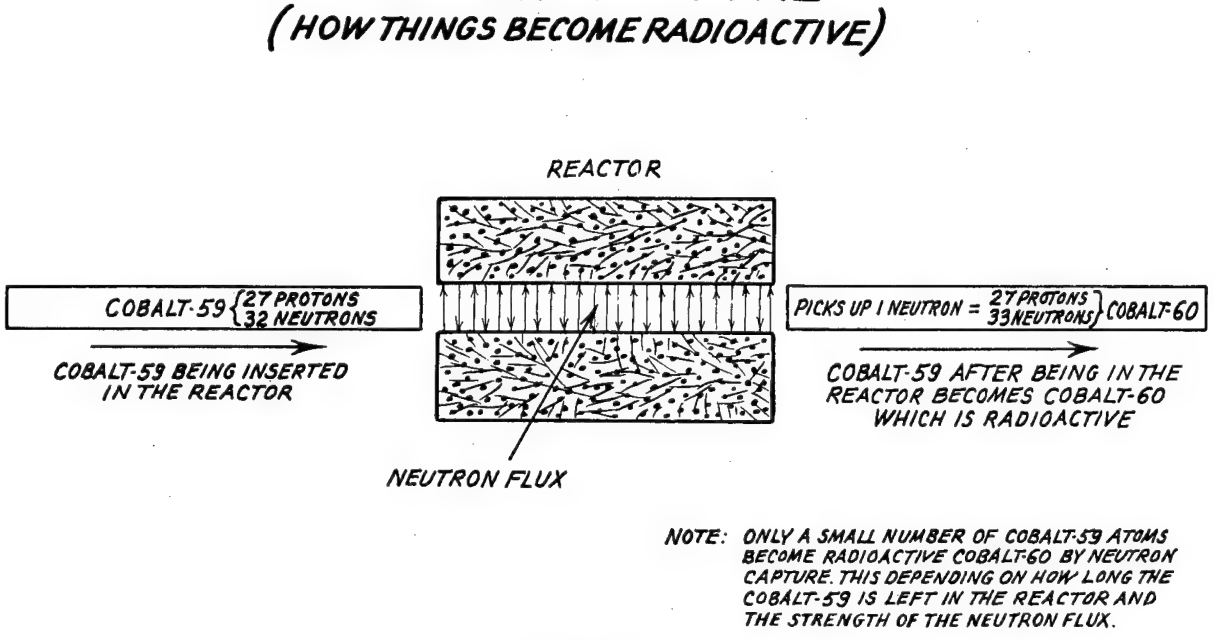


FIGURE 23

tron flux." A few of the atoms of cobalt, possibly one in a billion, capture neutrons and now have 33 neutrons instead of 32. These atoms are no longer cobalt 59, as we find it in nature, but cobalt 60. Cobalt 60 is radioactive, gives off gamma radiation, some beta radiation, and has a half-life of about 5.4 years.

When we take our sample of cobalt out of the reactor, it is still cobalt chemically; possibly one-billionth of it is radioactive cobalt. It would be extremely difficult to separate the radioactive cobalt from the nonradioactive cobalt, so we don't even try. The cobalt 60, as it is now called, is widely used for sources of penetrating external radiation, such as the radiography of casting, for deep therapy of cancer patients, etc. The cobalt was made radioactive by *neutron capture.*

Instead of cobalt, let us insert into our reactor some mercury 200. Mercury 200 has 80 protons and 120 neutrons. In the reactor, a tiny fraction of the atoms of mercury capture a neutron. They now have 80 protons and 121 neutrons.

It so happens that this mercury 201, when excited, throws out a proton, leaving us with 79 protons and 121 neutrons. Since we have changed the number of protons, we have changed the nature of the substance. These are no longer atoms of mercury, but atoms of the substance with 79 protons in the nucleus—gold. We have made gold 200, a radioactive isotope of gold. Since it is a different element from mercury, we can separate it by chemical means. This is shown in figure 24.

We have seen, therefore, that to make substances radioactive, we must subject them to a tremendous bombardment of atomic particles, such as neutrons in a nuclear reactor. There is another very precise way in which small quantities of radioisotopes can be created. Instead of the shotgun technique of the nuclear reactor, we can set up a target material and bombard it with nuclear particles at high speed. We get the particles up to high speed by whirling them around and around, as we would do with a slingshot. Machines which do this are called particle accelerators. Some

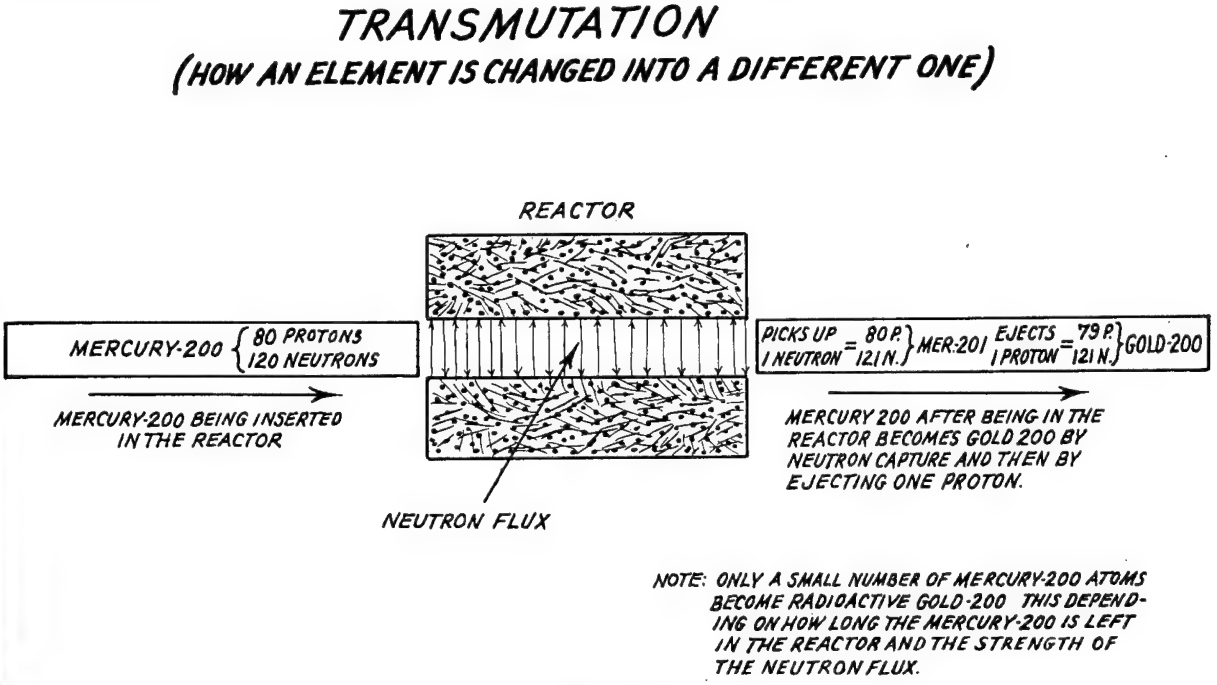


FIGURE 24

types of particle accelerators, such as the linear accelerator, get the particle going at high speed, but in a straight line rather than around and around in a circle.

We can get radioactive isotopes, therefore, as *fission products* by gathering up and separating out the fission products from the waste material of an atomic reactor; by *neutron capture* in which the target material captures a neutron but is not changed to another substance; and by *transmutation*, that is, by the changing of one element to another, as we have seen in the case of the mercury.

Things cannot be made radioactive by being subject to gamma radiation. Radioactivity is not induced in materials contaminated with radioactive substances. They are made radioactive by being subject to an intense neutron flux.

Return to "sketch D" of figure 21, a so-called subcritical mass; that is, an insufficient amount of material to sustain chain reaction.

Suppose we surround this material with a substance which causes neutrons to bounce back into the fissionable material. So to speak, we put the cushion upon the billiard table. We see that very few neutrons would then escape, and, in effect, the neutrons would have more than one chance to effect a collision with a target. Such a material is called a reflector, and, of course, it is designed into the construction of an atomic reactor in order to conserve the neutrons.

Our interest in reflection is the fact that many common substances, such as those rich in hydrogen, or other light elements, are good neutron reflectors, and, therefore, accidentally placing a material which can cause neutron reflection close to a subcritical mass of material might conceivably bring about a nuclear chain reaction.

For neutrons to be able to enter an atom and bring about fission, it is necessary that they be traveling at just the proper speed. Materials which are used to slow down the neutrons to the proper speed are called moderators. The accidental mixing of a moderator with a fissionable material might bring about such a

condition. For instance, water is both a reflector and a moderator of neutrons. A bucket of chips of fissionable material might be a subcritical mass. Filling the bucket with water, however, might bring about enough moderation and reflection of neutrons to change the situation to a critical mass condition.

What does all of this mean to us from the *practical safety* point of view? All three fatal accidents due to radiation in the atomic energy program took place in connection with the handling of fissionable materials. Figure 25 shows what happened when sufficient reflection to bring about criticality, was provided accidentally.

When fissionable materials are handled in our plants, it is necessary that we strictly comply with all regulations which are laid down. Naturally, the regulations take advantage of the various factors of spacing, shape, moderation, reflection, etc., which we have discussed. For instance, fissionable materials in storage are spaced certain distances apart. Where several projects are going on in a plant, there must be control of the movement of the materials within the plant; otherwise, a man from project A returning some material to the vault could conceivably pass a man from project B removing some material from the vault in a corridor and the exact situation be set up for a spontaneous chain reaction. The situation need exist only for a fraction of a second for an accident to happen.

Each individual operation must be carefully studied by personnel trained in the field of criticality. When they have completed their study, they lay down regulations for the safe conduct of the operation. Very many safety factors are built in, and basic to their safety consideration is that at least two entirely un-

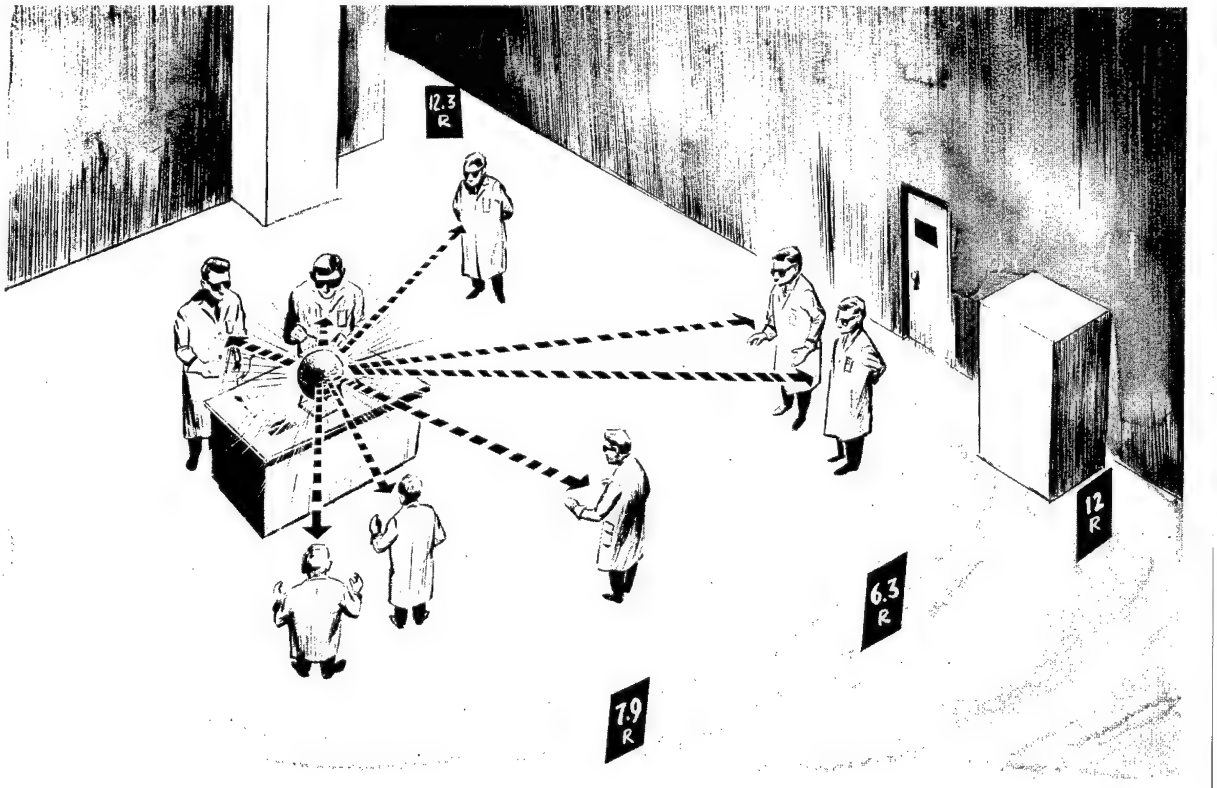


FIGURE 25.—May 1946; one man was killed in this criticality accident. The others were injured in varying degrees, but survived.

related precautions must be violated to set the stage for an accident.

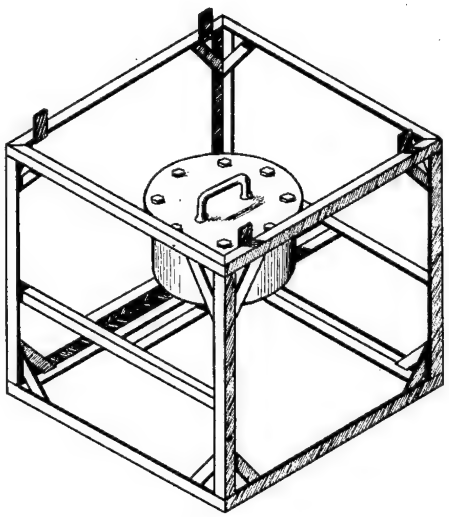
In many other fields of safety, we are constantly bombarded with the philosophy that the man on the job is his own best safety engineer, since he best knows the hazards of the job. This is not true of criticality safety. In this area, we must get "the word" from the man qualified to give it, and then follow it out to the letter. If some circumstance arises which makes it impossible for us to carry out the precautions as previously laid down, we cannot use our own judgment and modify the situation. We must return to the man who made the rule, explain our circumstances, and ask him for a new set of rules.

Materials may look the same and may even be called by the same name, but may vary greatly in their criticality characteristics due to the assay of the material, the presence or absence of poison, the density of the material, the shape of the material, etc. So, we cannot draw the conclusion that the job we are working on this week is the same as the one we did last week. We cannot assume that it is permissible to transfer a job from lathe No. 1 to lathe No. 2 because lathe No. 1 has broken down, even though we were allowed to do so last week when lathe No. 1 broke down.

In the transportation of fissionable material, it is obvious that precautions must be taken to prevent two or more subcritical masses from coming together as a result of an accident and creating a critical mass situation. Since water is a moderator and a reflector, there is hazard in the fact that the vehicle may be submerged entirely in water.

Accidents are guarded against by a number of precautions taken in transportation, among them the construction of containers called birdcages. Figure 26 shows a typical birdcage. The purpose of the birdcage, which is very heavily built, is to keep subcritical masses of fissionable material from approaching each other any closer than the outer limits of the birdcage.

For experimental work in atomic energy, it is often necessary that a source of neutrons be provided. Such sources are made up from alpha emitters, such as radium or polonium, mixed with beryllium. When an energetic particle from the polonium strikes the beryllium, a neutron is knocked out. Such sources



TYPICAL "BIRDCAGE" USED FOR SHIPPING FISSIONABLE MATERIALS

FIGURE 26

present a neutron radiation hazard in the body which they might strike, though the principal problem has been the formation of cataracts in the eyes of scientists who looked directly into neutron beams.

We saw that lead and other such materials are used for gamma radiation shielding because of the large number of electrons. An electron, of course, is not much help in stopping a neutron. To stop a neutron, we need an element which looks as much like a neutron as possible, so we will get a so-called billiard ball collision—that is, there will be an almost complete transfer of energy from the flying neutron to the particle trying to stop it.

The element which looks most like a neutron is hydrogen, which consists of one proton. Therefore, hydrogenous materials are used for neutron shielding. The cheapest, commonly available such material is paraffin, which has a high hydrogen content. Paraffin-filled containers are used for the shipment of neutron sources. Paraffin and water, which also contains large amounts of hydrogen, are used for shielding around devices, such as cyclotrons.

Special instruments and film badges, sensitive to neutrons, are used where there are neutron hazards.

The Safety and Fire Protection Branch, USAEC, plans to prepare a series of Parts II to this publication relating the material contained herein to the specific problems of various fields of endeavor such as fire departments, police departments, transportation, etc. Address inquiries to: Chief, Safety and Fire Protection Branch, USAEC, Washington 25, D.C.

Appendix A

101 ATOMIC TERMS AND WHAT THEY MEAN

(We are grateful to the Esso Research and Engineering Company for permission to reprint "101 Atomic Terms and What They Mean")

accelerator A device for imparting very high velocity to charged particles such as *electrons** or *protons*. These fast particles can penetrate matter and are known as *radiation*. Fast particles of this type are used in research or to study the structure of the *atom* itself.

activation Making a substance artificially *radioactive* in an *accelerator* such as a *cyclotron* or by *bombarding* it with *neutrons*.

alpha particle (alpha ray, alpha radiation) A small electrically charged particle of very high velocity thrown off by many *radioactive* materials, including *uranium* and *radium*. It is identical with the *nucleus* of a helium *atom* and is made up of two *neutrons* and two *protons*. Its electric charge is positive and twice as great as that of an electron.

atom The tiny "building block" of nature. All materials are made of atoms. The *elements*, such as iron, lead and sulfur, differ from each other because they contain different atoms. Atoms are unbelievably small. No one has ever seen one. There are six sextillion (6 followed by 21 zeros) atoms in an ordinary drop of water. The word "atom" comes from the Greek word meaning indivisible. Now we know it can be split and consists of an inner core (*nucleus*) surrounded by *electrons* which rotate around the nucleus like the planets around the sun.

atomic energy Energy released in *nuclear reactions*. Of particular interest is the energy released when a *neutron* splits an atom's *nucleus* into smaller pieces (*fission*) or when two nuclei are joined together under millions of degrees of heat (*fusion*). "Atomic energy" is really a popular misnomer. It is more correctly called "*nuclear energy*."

atomic number The number of *protons* (positively charged particles) found in the *nucleus* of an *atom*. All *elements* have different atomic numbers. The atomic number of hydrogen is 1, that of oxygen 8, iron 26, lead 82, *uranium* 92.

atomic theory Since the time of the ancient Greeks man has held the theory that all matter is composed of tiny, invisible particles called *atoms*. It remained for the chemists and physicists of the 19th and 20th centuries to verify the existence of the atom and the validity of the atomic theory.

atomic weight The atomic weight is approximately the sum of the number of *protons* and *neutrons* found in the *nucleus* of an atom. The atomic weight of oxygen, for example is approximately 16 (actually it is 16.0044)—it contains 8 neutrons plus 8 protons. Aluminum is 27—it contains 14 neutrons and 13 protons.

atom smasher A machine (an *accelerator*) that speeds up atomic and sub-atomic particles so that they can be used as projectiles to literally blast apart the *nuclei* of other *atoms*.

autoradiography Self-portraits of *radioactive sources* made by placing the radioactive material next to photographic film. The radiations fog the film leaving an image of the source. It was such self-portraits that led to the discovery of radioactivity.

background Background *radiation* is always detected by a counter. It is caused by radiation coming from *sources* other than the *radioactive* material to be measured. This "background" is primarily due to cosmic rays which constantly bombard the earth from outer space.

beta particle (beta radiation) A small electrically charged particle thrown off by many *radioactive* materials. It is identical with the *electron* and possesses the smallest negative electric charge found in nature. Beta particles emerge from radioactive material at high speeds, sometimes close to the speed of light.

betatron A large doughnut-shaped *accelerator* in which *electrons* (*beta particles*) are whirled through a changing magnetic field gaining speed with each trip and emerging with high energies. Energies of the order of 100 million *electron volts* have been achieved. The betatron produces artificial beta radiation.

bev A billion *electron volts*. An *electron* possessing this much energy travels with a speed close to that of light—186,000 miles a second.

bevatron A huge circular *accelerator* such as the one located at the University of California. *Protons* are whirled through the 160-foot "doughnut" between the poles of a magnet weighing 13,000 tons. It is designed to produce energies of 10 billion *electron volts*.

Italics indicate key words defined in this glossary.

binding energy The energy which holds the *neutrons* and *protons* of an atomic *nucleus* together.

bombardment Shooting *neutrons, alpha particles* and other high energy particles at atomic *nuclei* usually in an attempt to split the nucleus or to form a new *element.*

breeder A *reactor* which is producing more atomic fuel than it is consuming. A non*fissionable isotope, bombarded* by *neutrons,* is transformed into a fissionable material, such as *plutonium,* which can be used as fuel. Scientists are working toward the day when all the material burned in reactors will be replaced through this process.

Cerenkov radiation An eerie blue glow given off by *electrons* traveling in a transparent material such as water. It is this *radiation* which is visible during the operation of some nuclear *reactors.*

chain reaction When a *fissionable nucleus* is split by a *neutron* it releases energy and one or more neutrons. These neutrons split other fissionable nuclei releasing more energy and more neutrons making the reaction self-sustaining.

charge The fuel (*fissionable* material) placed in a *reactor* to produce a *chain reaction.*

cloud chamber A glass-domed chamber filled with moist vapor. When certain types of atomic particles pass through the chamber they leave a cloud-like track much like the vapor trail of a jet plane. This permits scientists to "see" these particles and study their motion.

cobalt 60 A *radioactive isotope* of the *element* cobalt. Cobalt 60 is an important source of *gamma radiation* and is used widely in research.

coffin A thick-walled container (usually lead) used for transporting *radioactive* materials.

compton effect The glancing collision of a *gamma ray* with an *electron.* The gamma ray gives up part of its energy to the electron.

control rod A rod used to control the power of a nuclear *reactor.* The reactor functions through the splitting of nuclear fuel by *neutrons.* The control rod absorbs neutrons which would normally split *atoms* of the fuel. Pushing the rod in reduces the release of atomic power. Pulling out the rod increases it.

converter A *reactor* which uses one kind of fuel and produces another. For example a converter charged with *uranium isotopes* might consume Uranium 235 and produce *plutonium* from Uranium 238.

core The heart of a nuclear *reactor* where the *nuclei* of the fuel *fission* (split) and release energy. The core is usually surrounded by a reflecting material which bounces stray *neutrons* back to the fuel.

cosmotron A huge *accelerator,* one of the atomic "guns," located at Brookhaven National Laboratory. It speeds up particles to the billion *electron volt* range. The Brookhaven machine has a magnet weighing 2,200 tons.

counter A device for counting nuclear disintegrations to measure *radioactivity.* The signal which announces a disintegration is called a count.

critical mass The amount of nuclear fuel necessary to sustain a *chain reaction.* If too little fuel is present too many *neutrons* will stray and the reaction will die out.

curie A measure of the rate at which a *radioactive* material throws off particles. The radioactivity of one gram of *radium* is a curie. It is named for Pierre and Marie Curie, pioneers in radioactivity and discoverers of the *elements* radium, radon, and polonium.

cutie-pie A portable instrument equipped with a direct reading meter used to determine the level of *radiation* in an area.

cyclotron A particle *accelerator.* In this atomic "merry-go-round" atomic particles are whirled around in a spiral between the ends of a huge magnet gaining speed with each rotation in preparation for their assault on the target material.

decay When a *radioactive atom* disintegrates it is said to decay. What remains is a different *element.* An atom of polonium decays to form lead, ejecting an *alpha particle* in the process.

deuterium *Heavy hydrogen.* The *nucleus* of heavy hydrogen is a *deuteron.* It is called heavy hydrogen because it weighs twice as much as ordinary hydrogen.

deuteron The *nucleus* of an *atom* of *heavy hydrogen* containing one *proton* and one *neutron.* Deuterons are often used as atomic projectiles.

dosimeter (dose meter) An instrument used to determine the *radiation* dose a person has received.

electron A minute atomic particle possessing the smallest amount of negative electric charge found in nature. In an *atom* the electrons rotate around a small *nucleus.* The weight of an electron is so infinitesimal that it would take 500 octillions (500 followed by 27 zeros) of them to make a pound. It is only about a two-thousandth of the mass of a *proton* or *neutron.*

electron volt (ev) A small unit of energy. An *electron* gains this much energy when it is acted upon by one volt.

element A basic substance consisting of a "family" of naturally occurring *isotopes.* For example, hydrogen, lead and oxygen are elements. All *atoms* of an element contain a definite number of *protons* and thus have the same *atomic number.*

film badge A piece of masked photographic film worn like a badge by nuclear workers. It is darkened by nuclear *radiation,* and radiation exposure can be checked by inspecting the film.

fission The splitting of an atomic *nucleus* into two parts accompanied by the release of a large amount of *radioactivity* and heat. Fission reactions occur only with heavy *elements* such as *uranium* and *plutonium.*

fissionable A *nucleus* which undergoes *fission* under the influence of *neutrons*, even of very slow neutrons. *Uranium* 235, an *isotope* of uranium with mass number 235, is fissionable. *Plutonium* is also fissionable.

fusion The joining of atomic *nuclei* to form a heavier nucleus, accomplished under conditions of extreme heat (millions of degrees). If two nuclei of light *atoms* fuse, the fusion is accompanied by the release of a great deal of energy. The energy of the sun is believed to be derived from the fusion of hydrogen atoms to form helium.

gamma rays (gamma radiation) The most penetrating of all *radiations.* Gamma rays are very high energy *X-rays.*

geiger counter A gas-filled electrical device which detects the presence of *radioactivity* by counting the formation of *ions.*

half-life A means of classifying the rate of *decay* of *radioisotopes* according to the time it takes them to lose half their strength (intensity). Half lives range from fractions of seconds to billions of years. *Cobalt 60*, for example, has a half-life of 5.3 years. A *radioactive* material loses half its strength when its age is equal to its half-life.

heavy hydrogen Same as *deuterium.*

heavy water Water which contains *heavy hydrogen* (*deuterium*) instead of ordinary hydrogen. It is widely used in *reactors* to slow down *neutrons.*

hot A colloquial term meaning highly *radioactive.*

ion Usually an *atom* which has lost one or more of its *electrons* and is left with a positive electrical charge. There are also negative ions, which have gained an extra electron.

ionization chamber A device roughly similar to a *geiger counter* and used to measure *radioactivity.*

isotope Two *nuclei* of the same *element* which have the same charge but different masses are called isotopes. They contain the same number of *protons* but a different number of *neutrons. Uranium* 238 contains 92 protons and 146 neutrons while the isotope U^{235} contains 92 protons and 143 neutrons. Thus the *atomic weight* (atomic mass) of U^{238} is three higher than that of U^{235}.

kev Kilo *electron* volts or 1,000 electron volts. A unit of energy.

kilocurie 1,000 *curies.* A unit of *radioactivity.*

linear accelerator A machine for speeding up charged particles such as *protons.* It differs from other *accelerators* in that the particles move in a straight line at all times instead of in circles or spirals.

master slave manipulators Mechanical hands used to handle *hot* materials. They are remotely controlled from behind a protective *shield.*

meson A particle which weighs more than the *electron* but generally less than the *proton.* Mesons can be produced artificially. They are also produced by cosmic *radiation* (natural radiation coming from outer space). Mesons are not stable—they disintegrate in a fraction of a second.

mev Million *electron volts.*

milliroentgen One one-thousandth of a *roentgen.* A *roentgen.* A unit of *radioactive* dose.

moderator A material used to slow *neutrons* in a *reactor.* These slow neutrons are particularly effective in causing *fission.* Neutrons are slowed down when they collide with *atoms* of light *elements* such as hydrogen and carbon, two common moderators.

molecule The smallest unit of a compound. A water molecule consists of two hydrogen *atoms* combined with one oxygen atom. Hence the well-known formula, H_2O.

monitor A *radiation* detector used to determine whether an area is safe for workers. A *cutie-pie* is a portable monitor.

neutron One of the three basic atomic particles. The neutron weighs about the same as the *proton,* and, as its name implies, has no electric charge. Neutrons make effective atomic projectiles.

nuclear bombardment The shooting of atomic projectiles at *nuclei* usually in an attempt to split the *atom* or to form a new *element.*

nuclear energy The energy released in a *nuclear reaction,* such as *fission* or *fusion.* Nuclear energy is popularly, though mistakenly, called *atomic energy.*

nuclear reaction Result of the *bombardment* of a *nucleus* with atomic or sub-atomic particles or very high energy *radiation.* Possible reactions are emission of other particles or the splitting of the nucleus (*fission*). The *decay* of a *radioactive* material is also a nuclear reaction.

nucleonics The application of nuclear science and techniques in physics, chemistry, astronomy, biology, industry and other fields.

nucleus The inner core of the *atom.* It consists of *neutrons* and *protons* tightly locked together.

pair production The conversion of a *gamma ray* into a pair of particles—an *electron* and a *positron.* This is an example of direct conversion of energy into matter according to Einstein's famous formula: $E=mc^2$; (energy) = (mass) x (velocity of light)^2.

photoelectric effect Occurs when an *electron* is knocked out of an *atom* by a light ray or *gamma ray.* This effect is used in an "electric eye". Light falls on a sensitive surface knocking out electrons which can then be detected.

photon A bundle (quantum) of *radiation.* Constitutes, for example, *X-rays* and light. In certain processes *gamma rays* behave as photons.

pig A container (usually lead) used to ship or store *radioactive* materials. The thick walls protect the person handling the container from *radiation.*

pile A nuclear *reactor.* Called a pile because the earliest reactors were "piles" of graphite blocks and *uranium slugs.*

pitchblende An ore containing both *uranium* and *radium.* The Curies had to purify tons of pitchblende to obtain a barely visible speck of radium.

plutonium A heavy *element* which undergoes *fission* under the impact of *neutrons.* It is a useful fuel in nuclear *reactors.* Plutonium does not occur in nature but can be produced and "burned" in reactors.

positron A particle which has the same weight and charge as an *electron* but is electrically positive rather than negative. The positron's existence was predicted in theory years before it was actually detected. It is not stable in matter.

proton One of the basic particles of the atomic *nucleus* (the other is the *neutron*). Its charge is as large as that of the *electron,* but positive.

Q-value The energy liberated or absorbed in a *nuclear reacton.*

rabbit A capsule which carries samples in and out of an atomic *reactor* through a pneumatic tube. Purpose is to permit study of the effect of intense *radiation* upon various materials.

radiation (radioactivity) The emission of very fast atomic particles or rays by *nuclei.* Some *elements* are naturally radioactive while others become radioactive after *bombardment* with *neutrons* or other particles. The three major forms of radiation are *alpha, beta* and *gamma,* named for the first three letters of the Greek alphabet.

radiochemistry That phase of chemistry concerned with the properties and behavior of *radioactive* materials.

radioisotope A *radioactive isotope* of an *element.* A radioisotope can be produced by placing material in a nuclear *reactor* and *bombarding* it with *neutrons.* Radioisotopes are being used today as *tracers* in many areas of science and industry and are at present the most important peacetime contribution of *atomic energy.*

radium One of the earliest known naturally *radioactive elements.* It is far more radioactive than *uranium* and is found in the same ores.

reactor An atomic "furnace". In a reactor, *nuclei* of the fuel undergo *fission* under the influence of *neutrons.* The fission produces new neutrons, and hence a *chain reaction.* This release large amounts of energy. This energy is removed as heat which may be used to make steam for use in generation of electricity.

roentgen A unit of *radioactive* dose, or exposure. The Atomic Energy Commission has established a conservative limit of exposure for the protection of atomic workers.

scintillation counter A device for counting atomic particles by means of tiny flashes of light (scintillations) which the particles produce when they strike certain crystals.

shield A wall which protects workers from harmful *radiations* released by radioactive materials.

slug A "fuel element" for a nuclear *reactor,* a piece of *fissionable* material. The slugs in large reactors consist of *uranium* metal coated with aluminum to prevent corrosion.

source Any substance which emits *radiation.* Usually refers to a piece of radioactive material conveniently packaged for scientific or industrial use.

synchrotron An *accelerator* used to achieve higher velocities for atomic particles than is possible in a conventional *cyclotron.*

thermonuclear reaction a *fusion* reaction, that is, a reaction in which two light *nuclei* combine to form a heavier *atom,* releasing a large amount of energy. This is believed to be the sun's source of energy. It is called thermonuclear because it occurs only at a very high temperature.

thorium A heavy *element.* When *bombarded* with *neutrons* thorium changes into *uranium* becoming *fissionable* and thus a source of *atomic energy.*

tracer A *radioisotope* which is mixed with a stable material. The radioisotope enables scientists to trace the material as it undergoes chemical and physical changes. Tracers are being used widely in science, industry and agriculture today. When *radioactive* phosphorous, for example, is mixed with a chemical fertilizer the radioactive substance can be traced through the plant as it grows.

tritium Often called hydrogen three. Extra heavy hydrogen whose *nucleus* contains two *neutrons* and one *proton.* It is three times as heavy as ordinary hydrogen and is *radioactive.*

unstable All *radioactive elements* are unstable since they emit particles and *decay* to form other elements.

uranium A heavy metal. The two principal *isotopes* of natural uranium are U^{235} and U^{238}. U^{235} has the only readily *fissionable nucleus* which occurs in appreciable quantities in nature, hence its importance as nuclear fuel. Only 1 part in 140 of natural uranium is U^{235}.

Van de Graaff accelerator An electrostatic generator—a particle *accelerator.* To obtain the voltage, static electricity is picked up at one end of the ma-

chine by a rubber belt and carried to the other end where it is stored.

X-ray Highly penetrating *radiation* similar to *gamma rays*. Unlike gamma rays, X-rays do not come from the *nucleus* of the *atom* but from the surrounding *electrons*. They are produced by electron *bombardment*. When these rays pass through an object they give a shadow picture of the denser portions.

"Z" Symbol for *atomic number*. An *element's* atomic number is the same as the number of *protons* found in one of its *nuclei*. All *isotopes* of a given element have the same "Z" number.

Appendix B

Quantities of some commonly used radioisotopes required to equal either 500 or 10 millicuries arranged according to their half-life.[1]

Isotope	Half-life	Quantity [3] required to equal:	
		500 millicuries	10 millicuries
Argon 41	109 minutes	0.01 micrograms	0.0002 micrograms.
Potassium 42	12.4 hours	0.08 micrograms	.0016 micrograms.
Sodium 24	15.1 hours	0.06 micrograms	.0012 micrograms.
Gold 198	2.7 days	2.05 micrograms	.041 micrograms.
Iodine 131	8.1 days	4.1 micrograms	.082 micrograms.
Phosphorus 32	14.3 days	1.75 micrograms	.035 micrograms.
Chromium 51	27.8 days	0.55 micrograms	.011 micrograms.
Iron 59	45 days	10.2 micrograms	.204 micrograms.
Strontium 89	53 days	18 micrograms	.36 micrograms.
Iridium 192	74 days	5.5 micrograms	.11 micrograms.
Sulphur 35	87 days	11.5 micrograms	0.23 micrograms.
Polonium 210	138 days	111.5 micrograms	2.23 micrograms.
Calcium 45	163 days	27 micrograms	0.54 micrograms.
Zinc 65	250 days	65 micrograms	1.30 micrograms.
Iron 55	2.9 years	222 micrograms	4.43 micrograms.
Cobalt 60	5.3 years	440 micrograms	8.80 micrograms.
Krypton 85	10.3 years	5.2 milligrams	25 micrograms.
Hydrogen 3	12.5 years	0.05 milligrams	1 microgram.
Strontium 90	25 years	3.15 milligrams	63 micrograms.
Cesium 137	30 years	5.75 micrograms	115 micrograms.
Radium 226	1,620 years	0.5 gram	10 milligrams.
Carbon 14	5,800 years	0.12 gram	2.3 milligrams.
Plutonium 239	24,000 years	8.0 gram(¼ oz.)	160 milligrams.
Uranium 235	7.1×10^8 years [2]	525 lbs	10.5 lbs.
Uranium 238	4.5×10^9 years	3,300 lbs	66 lbs.
Thorium 232	1.4×10^{10} years	5 tons	200 lbs.

[1] These weights are for the pure radioisotope. In practice, the active material is generally mixed or alloyed with a quantity of inactive material and may constitute only a small fraction of the bulk. Also, self or internal shielding may reduce the external radiation considerably.

[2] 10^8 etc. is merely shorthand for expressing large numbers—in this case 100,000,000 (eight ciphers)—so that $7.1\times10^8=710,000,000$ years.

[3] One gram equals 0.035 ounces avd. (approx. 1/28th of an ounce).
A milligram equals 0.000035 ounces (35 millionths of an ounce).
A microgram equals 0.000000035 ounces (35 billionths of an ounce).

GAMMA RADIATION LEVEL AT THREE FEET FROM 1 CURIE OF CERTAIN RADIOISOTOPES

	R/Hr		*R/Hr*
Sodium 24	2. 31	Iridium 192	0. 61
Gold 198	. 30	Cobalt 60	1. 59
Iodine 131	. 28	Zinc 65	. 36
Iron 59	. 77	Cesium 137	. 43

BIBLIOGRAPHY

The following publications are available from the Superintendent of Documents, Government Printing Office, Washington 25, D.C.:

Handbook No. 42.—Safe Handling of Radioactive Isotopes, price $0.20.

Handbook No. 48.—Control and Removal of Radioactive Contamination in Laboratories, price $0.15.

Handbook No. 51.—Radiological Monitoring Methods and Instruments, price $0.20.

Handbook No. 52.—Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water, price $0.25.

Handbook No. 54.—Protection Against Radiations from Radium Cobalt 60, and Cesium 137, price $0.25.

Handbook No. 55.—Protection Against Betatron-Synchrotron Radiations up to 100 Million Electron Volts, price $0.25.

Handbook No. 56.—Safe Handling of Cadavers Containing Radioactive Isotopes, price $0.15.

Handbook No. 58.—Radioactive-Waste Disposal in the Ocean, price $0.20.

Handbook No. 59.—Permissible Dose from External Sources of Ionizing Radiation, price $0.30.

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Radiation Safety and Major Activities in the Atomic Energy Programs, July–December 1956, price $1.25.

Some Effects of Ionizing Radiation on Human Beings, price $1.25.

Handbook of Federal Regulations Applying to Transportation of Radioactive Materials, price $0.25.

Radiation Safety Primer, price $0.25.

The following publications are available from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.:

A Summary of Accidents and Incidents Involving Radiation in Atomic Energy Activities, June 1945 through December 1955, price $0.45.

A Summary of Accidents and Incidents Involving Radiation in Atomic Energy Activities, January 1956 through December 1956, price $1.00.

The following publications are available from the Safety & Fire Protection Branch, USAEC, Washington 25, D.C.:

Radiation Safety Primer Instructors Handbook, single copies only, no charge.

The following publications are available in limited quantities from the Division of Licensing and Regulation, USAEC, Washington 25, D.C.:

Title 20, Code of Federal Regulations, All Parts.

An excellent source of basic data is "Selected Materials on Employee Radiation Hazards and Workmen's Compensation" published February 1959 by the Joint Committee on Atomic Energy, Congress of the United States. For sale by Superintendent of Documents, price $1.00.

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